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RESEARCH MEMORANDUM

APPLICATION OF A WINDSHIELD-DISPLAY SYSTEM TO THE LOW-ALTITUDE BOMBING PROBLEM

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

The development and flight evaluation of a tracking-type windshield display for use in a low-altitude bombing (LAB) system are described. Initially it was thought that the use of this display would lead to an improvement over the standard cross-pointer instrument in the repeatability of the specified maneuver and to a consequent improvement in bombing accuracy. However, comparison of random bomb miss distances of practice bombs dropped in the present tests showed little difference between the standard and the revised equipment. Subsequent statistical analyses of random bomb errors indicated that the contribution of flight-path tracking inaccuracies were small for all test cases, and that these errors could be attributed primarily to sources other than tracking - for example, to inaccuracies in the prediction and compensation for wind effects. Thus it appeared that any effects of the revised equipment on bombing accuracy were obscured by large random errors from other sources which were unaffected by changing to the tracking-type windshield display.

The windshield display was highly regarded by the pilots, who considered it a natural one to learn and to fly with confidence. It thus appears that the windshield display might be fruitfully applied to other instrument flight problems in which maneuver programming and tracking accuracy are of greater over-all importance.

INTRODUCTION

The design and flight evaluation of an airborne target simulator for use in tracking studies of fighter-type airplanes equipped with optical gunsights have recently been reported (ref. 1). In this equipment the target airplane was represented by a movable dot of light projected on the windshield of the test airplane. This simulated target dot, which was tracked by the pilot with a fixed gunsight dot, not only was stabilized against own ship's oscillations, but could be programmed at precomputed rates in space to represent selected target maneuvers. This windshield tracking display can be thought of as forming a pitch and yaw flight-attitude instrument. The moving target dot is oriented as specified by the program unit, while the fixed pip indicates the actual orientation of the aircraft reference line. Thus, tracking errors can be interpreted as pitch and yaw attitude errors. Since pilots were able to hold these attitude errors down to a few mils in various simulated target-tracking runs, it appeared that these programming and display principles might be applied with advantage to certain instrument flight problems.

For the present investigation a low-altitude bombing problem was selected as an example for study of the instrument-flight application of target-simulator principles. The low-altitude bombing (hereafter abbreviated LAB) attack requires the aircraft to approach the target at very low altitude and at high speed. At a predetermined point the pilot abruptly initiates a constant high-acceleration pull-up, continuing until the aircraft completes a half loop, and recovering with a diving roll-out for escape. A special pitch-attitude gyro mounted in the aircraft initiates the bomb release automatically at a predetermined pitch angle during the pull-up, "lofting" the bomb toward the target. For a successful delivery, the aircraft must follow a specified variation with time of airspeed and normal acceleration, and must remain in the original vertical plane throughout the maneuver. In the conventional LAB system used by the Navy, the guidance information is presented to the pilot on a cross-pointer indicator mounted in the aircraft instrument panel. The position of the horizontal needle represents normal-acceleration error as sensed by an accelerometer and bridge-balancing circuit. The position of the vertical needle represents combined roll- and yaw-angle error as sensed by a special gyro. In the windshield-display system to be described, the cross-pointer was replaced by a fixed and a moving dot on the windshield. The relative motions of the dots in elevation and azimuth were measures of acceleration and roll-yaw errors, respectively. In addition, the constant step-input-acceleration command used with the standard system was replaced by a continuous time-history type of acceleration command.

The equipment was designed and fabricated at Ames Aeronautical Laboratory and installed in a Grumman F9F-8 airplane from Naval Air Development Squadron Five (VX-5) at Moffett Field, California. Flight tests were conducted by VX-5 personnel with technical assistance from Ames. The flight tests were directed at establishment of appropriate system sensitivities, evaluation of pilots' ability to fly the prescribed maneuver, and a limited evaluation of miss distances from practice bomb-dropping tests conducted at the Naval Ordnance Test Station, China Lake, California. The equipment and flight-test results are described herein.

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DESCRIPTION OF APPARATUS

Design Concepts

A profile view of the flight path and the time histories of the acceleration and airspeed for an idealized low-altitude bombing attack are shown in figure 1. As the aircraft passes over a predetermined point, called the initiation point, the pilot depresses the stick switch which starts a timing mechanism. When an instrument indication is received, the pilot enters the maneuver by abruptly pulling up to 4g in two seconds. The pilot maintains 4g until limited by the decreasing maximum lift capability of the aircraft. The airplane is then flown along the buffet boundary to complete a half loop, and recovery is made with a diving roll-out for escape. The bomb is released during the 4g portion of the pull-up at a preselected angle ranging from 40° (termed medium angle or "loft" release) to 120° (termed high angle or "over-the-shoulder" release, abbreviated O/S).

The Aero 18A Armament Control System, described in reference 2, is currently employed by the Navy to fly this attack. A simplified diagram of this system is shown in figure 2(a). The guidance information required to perform the maneuver of figure 1 is displayed to the pilot on a cross-pointer indicator that is mounted in the instrument panel. The horizontal needle indicates errors in normal acceleration, and the vertical needle indicates combined errors of roll and yaw angles. The horizontal meter movement and the normal-accelerometer transducer are connected in a bridge circuit which is adjusted for balance when 4g is applied to the accelerometer. Any deviation from 4g causes the meter to deflect from the zero position. In the roll-yaw indicator circuit, the two gyro gimbal pickoffs are in separate bridge arrangements, with the outputs combined for a single meter indication. The roll-yaw gyro is a free gyro with its spin axis mounted parallel to the pitch axis of the aircraft. The roll gimbal measures essentially the conventional roll or bank angle; however, the yaw gimbal does not measure the conventional heading angle or yaw, but rather the angle between the aircraft reference axis and the vertical reference plane, as measured in the inclined plane of the aircraft. In the operation of this equipment the pilot begins the maneuver by depressing the stick switch. The pull-up command is indicated by the horizontal needle dropping to show a 3g error in acceleration. The pilot then attempts to pull up to 4g (and thus level the needle) in the required 2 seconds. When the aircraft can no longer maintain 4g, the pilot disregards the horizontal needle and flies along the buffet boundary. During this same period the pilot attempts to keep the vertical needle centered at all times. The bomb is released automatically at preset pitch angles by a separate pitch-attitude gyro.

Practice bomb drops using this and similar equipment have often resulted in unacceptably large miss distances. At the time the present

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investigation was initiated, it was believed that these excessive bombing errors were due in large part to the inability of the pilot to repeat the specified maneuver. It appeared that maneuver repeatability and, hence, bombing accuracy, might be improved through the use of a more practical and accurately specified acceleration-command pattern and replacement of the small cross-pointer instrument with a large and sensitive tracking-type display.

The Ames windshield display was designed with these thoughts in mind. To facilitate comparisons of the two systems and to minimize development difficulties, much of the standard LAB system was retained. The system transducers and signal flow patterns are essentially identical, as are the cockpit operations and procedures. The primary differences are the replacement of the cross-pointer by a two-dot tracking-type display and the substitution of a precision programming device for the step-input constant g command. A simplified diagram of the windshield-display system is shown in figure 2(b). The programmer (fig. 3) consists of a motor-driven face cam which has been profiled in proportion to the desired acceleration time history in figure 1 and a follower which positions an electrical pickoff. This output is compared continuously with that from an accelerometer transducer similar to that used in the standard system. The resulting acceleration error signal is used to drive the display. In an effort to reduce an early tendency of the pilots to fly bias acceleration errors, an acceleration-error-signal integrator was added during the program, and was used on a number of flights. In effect, it adds a display actuating signal proportional to the time integral of acceleration error. Roll and yaw error signals are provided by a gyro unit identical to that used in the standard system. The error signals are sent to an optical display unit which was constructed from components of an A-1 armament control system (fig. 4). Here, a servo-driven gimballed mirror displaces a moving dot on the windshield in proportion to the error signals, in elevation for acceleration errors and in azimuth for combined roll-yaw errors. Controls were provided to enable the pilot to make independent adjustment of acceleration, roll, and yaw error sensitivities (dot motion per unit error) over wide ranges. The sight head also provides, through the use of a fixed mirror, the second dot which serves as a fixed instrument reference. Thus, the pilot's task is to track continuously the moving dot with the fixed dot to minimize deviations from the desired maneuver. The system block diagram of figure 5 and various components are described in more detail in the Appendix.

Installation in the Test Airplane

The Ames windshield-display LAB system was installed in a Grumman F9F-8 aircraft, BuAer No. 131086, assigned to Navy Squadron VX-5 (fig. 6). A close-up view of the equipment mounted in the nose of the airplane is shown in figure 7. All the ammunition containers and some of the ammunition feed chutes were removed to make room for the installation. With the exception of the cockpit units and acceleration transducer, the entire system - the inverter, electronics, power supplies, switching circuits, and the complete instrumentation system - was located in the nose. The acceleration transducer was mounted in the nose wheel well about 3 feet forward of the aircraft center of gravity. Figure 8 is a photograph of the modified sight-head installation used to project the windshield display. The sight head was mounted behind the instrument panel flush with the instrument shroud. The camera's combining glass forms the dot images for recording purposes, while the pilot's combining glass forms the dot images for direct viewing by the pilot. Both combining glasses had partially silvered surfaces to increase the apparent dot brilliance. The silvering on the pilot's glass was limited to a square inch so as not to impair normal forward visibility. The pilot's control panel (mounted in the right-hand cockpit console) is shown in figure 9. Located here were all the operational controls for the windshield display, except for the program initiation switch, which was located on the control stick.

Instrumentation

The windshield-display equipment included provisions for a recording oscillograph system. A sample record from the NACA nine-channel color oscillograph is shown in figure 10, in which the various traces are identified. Two other standard NACA recording instruments monitored airspeed, altitude, and normal acceleration. A chronometric instrument provided time correlation of all the records. The 16mm GSAP motion-picture camera shown in figure 5 photographed the dot motions at 16 frames per second as seen by the pilot. Selected frames of a typical run are shown in figure 11.

TESTS, RESULTS, AND DISCUSSION

The final portion of the flight-test program consisted of practice bomb drops made with the windshield-display low-altitude bombing system. These tests and a comparison of the miss-distance results with those from similar tests using the standard LAB system will be presented first. Prior to these final tests it was necessary, owing to the novelty of the Ames system, to perform extensive preliminary flight tests in order to familiarize the pilots with the new equipment and establish suitable values of system parameters. These tests will also be described and discussed, since they not only are pertinent to the present miss-distance evaluation but may also be of interest in other possible applications of the windshield-display concept.

Miss-Distance Evaluation Using Practice Bombs

Test conditions.- The bomb-drop tests using the windshield-display system were conducted on the C range, Naval Ordnance Test Station, China Lake, California. This range is situated on a flat desert area at 2,300 feet elevation and consists of target, control tower, and several spotting towers for measuring the position of bomb impacts by triangulation. Extending for 40,000 feet north and south of the target is a straight cleared path over which the approach to the target by the attacking aircraft is always made. Because of the initial low altitude of the maneuver, convection turbulence became severe during the heat of the day. To minimize rough-air effects, flight operations were begun shortly after dawn and were terminated at 11:00 a.m.; even so, several flights were terminated earlier because of severe turbulence.

The flight procedures used by Squadron VX-5 in evaluating the standard LAB system accuracies were used in the windshield-display-system bomb-drop tests. Runs on the target were made over the cleared path at an altitude of 100 feet and true airspeed of 450 knots. The program was initiated over a predetermined point marked by a brightly colored pylon for the loft delivery or directly over the target for the over-the-shoulder delivery. The aircraft was equipped to carry six 25-pound Mark 76 practice bombs which were released singly. The runs were made from alternate directions until all six bombs were expended. Under unusual lighting conditions it was sometimes necessary to perform all runs in one direction to avoid making the pull-up directly into the sun.

There were 14 practice bomb-drop flights made with the windshield-display system, with a total of 84 bombs dropped; 72 of these were useful for analysis purposes. Several of the bombs were eliminated from the analysis because of faulty pull-ups or initial miscalculation of the wind, errors which put the drops outside the target area. The flight tests were divided among the four major test conditions:

1. Loft release, integrator in (integrator connected)
2. Loft release, integrator out (integrator disconnected)
3. Over the shoulder, integrator in
4. Over the shoulder, integrator out

As discussed later, display sensitivities were held constant at previously selected values. For comparison, miss data for a representative sample were selected from a large number of bombs dropped by Navy Squadron VX-5 during an extensive evaluation of the standard LAB system. The same two pilots made the standard system drops over the same time span in the same type of aircraft. These pilots differed primarily in their experience levels with the windshield-display system; their experience with the normal system was about the same. One pilot conducted all the early evaluation and test flights of the Ames system, while the other pilot trained specifically as a second pilot for the later bomb-drop tests.

Measured miss distances.- Table I presents the basic bomb-drop data for both the windshield-display and normal system. The data are grouped according to flights, and the flights are grouped according to test conditions. The "Direction" column indicates the direction from which the run was initiated. "Range" is the miss distance along the aircraft line of flight, while "Deflection" is the miss distance at right angles to the line of flight, both taken from range measurements. The sign notation is conventional, forward and right being positive with respect to the run direction. In the reduction of these raw data, methods similar to those used by Squadron VX-5 were employed. To illustrate, figure 12 is a bomb plot for a typical flight, in which three bombs were dropped from one direction and three dropped from the opposite direction. The coordinates of the mean point of impact (m.p.i.) for all six bombs are termed "wind error," ascribed primarily to an error in estimating the average wind velocity during the period of flight. The coordinates of the m.p.i. for each group of three bombs, referred to the total m.p.i., are "system error," ascribed to systematic errors in the bombing system for that particular flight. The deviations of the individual bomb impact points from these group m.p.i. are termed "random errors," associated with variations from run to run. In the present case, emphasis was directed at analysis of random errors since, presumably, they are the only ones that would be affected appreciably by the variations in the LAB display system used in the present study. Range and deflection components of these random errors are tabulated in table I.

In addition to the random errors discussed above, a correction was made to the range-error component. This correction was made to compensate for a progressive range error between successive runs in the same direction, an effect noticed by the pilots during these flights. Review of the data verified this observation for both windshield-display and standard LAB systems. For example, examination of the south and north runs (runs 1, 3, 5 and 2, 4, 6, respectively) range errors for flights 10 and 11 shows a definite progression. Further examination indicated that these increases in range error from run to run were associated with changes in airplane gross weight due to fuel consumption during the test flight. Although this trend is not apparent in all flights (e.g., flight 13), it is believed that under more carefully controlled conditions it could be considered a predictable error rather than a random error of interest in the present investigation. This involved finding the average change between successive runs for all the flights of one flight condition, then applying this correction to each run. Although the data available from the present tests were not sufficient to permit accurate corrections, approximate corrections were applied to the range and radial errors. In addition to the tabular data, figure 13 presents plots of corrected random miss data grouped by flight condition. There is no separation by pilots because any small differences were submerged in random errors. The form of the probability distribution of range and deflection miss components about the m.p.i. are of interest for further statistical analysis which is discussed later;

accordingly, the corrected data were also plotted on probability paper, which yields a straight-line plot for normally distributed samples. Example probability plots are shown in figure 14.

The results of all the practice bomb drops are summarized in table II. Here the standard deviation of the range and deflection components is given for each of the flight conditions. For each case the standard deviations of the miss components were computed from the equations

$$\sigma_x = \sqrt{\frac{\sum_m \left(x - \bar{x}_n\right)^2}{\sum_m n}}$$

and

$$\sigma_y = \sqrt{\frac{\sum_m \left(y - \bar{y}_n\right)^2}{\sum_m n}}$$

where $\bar{x}_n$ and $\bar{y}_n$ are the mean values (coordinates of the m.p.i.) for each group of n bombs dropped in one direction during a flight, x and y are range and deflection coordinates of an individual bomb impact, and m is the number of groups in each case. The mean radial error (m.r.e.), also given in table II, was computed from the formula

$$\text{m.r.e.} = \frac{\sum_m \sqrt{\left(x - \bar{x}_n\right)^2 + \left(y - \bar{y}_n\right)^2}}{\sum_m n}$$

As a check on these numerical calculations, the standard deviations of x and y were also derived from the faired cumulative probability curves, such as figure 14. Values determined in this manner agreed with the values tabulated in table II within 2 percent. The m.r.e. values were successfully checked in a similar manner.

In the discussion of the measured bomb miss distances, attention will be concentrated on the m.r.e. data of table II, the final measure of random bomb error. These m.r.e. data give apparently conflicting impressions of the effect of the normal-acceleration-error integrator on the windshield-display-system results. In the over-the-shoulder (O/S), integrator-out maneuver, the m.r.e. was less, primarily due to a large reduction in the measured deflection errors. This reduction is believed to be of doubtful significance since the display roll-yaw channel and the associated tracking problem were identical for the two cases and since the integrator-out results are based on only 11 test drops. The large difference in the number of runs was not intentional, but arose from difficulties in controlling the flight program at a distant station. For the loft maneuver, the greater m.r.e. with integrator out is due primarily to larger measured range components. However, this was one of the conditions where the gross weight error correction was large so that the resulting m.r.e. was virtually the same. Since from the above discussion it does not appear that the integrator has a large effect, the integrator-in and -out data have been combined to facilitate comparison with the standard LAB system data.

A comparison of the windshield display to the standard system in table II shows the trends to be the same for either the measured m.r.e. or the m.r.e. corrected for gross weight. For the O/S maneuver the windshield display shows a modest reduction in m.r.e. over the standard system. No definite or readily apparent reason can be given for this effect of flight maneuver on the relative performance of the two systems. The improvement shown by the windshield display for the longer O/S maneuver may be attributed to the refined programming and sensitive display; however, these apparent advantages may not have much effect on the loft maneuver where the time is so short (approximately 7 seconds) and the initial acceleration rise so abrupt that experienced pilots appear to fly the maneuver with little real use of the instruments.

<u>Analyses of miss distances</u>.- The relatively small differences between the m.r.e. values for the windshield display and the standard system were rather surprising in view of the major changes in display, maneuver programming, and associated pilot technique. This lack of improvement in bombing accuracy led to the suspicion that the inability to repeat precisely the acceleration and roll-yaw time history is only one of several potentially significant sources of error. Presumably, the only source of bomb error directly affected by test changes in the LAB system flight display would be the accuracy and repeatability with which the selected test maneuver could be flown, in terms of the tracking errors, that is, the difference between desired and measured normal acceleration, roll- and yaw-angle time histories. Accordingly, the estimate of the bomb miss due to tracking errors was of interest in attempting to interpret and compare the measure random bomb errors. With this in mind, tracking-error time histories, such as those in figures 16, were derived from oscillograph records (fig. 10) for each bomb run. These data were then used in various computational procedures designed to "predict" the bomb miss associated with tracking errors alone.

No strong and consistent positive correlation between measured and predicted bomb miss distances was ever attained, despite numerous plausible variations made in the prediction method. In all cases, the standard deviation of the predicted bomb miss due to tracking errors was much less than the measured value, in most cases from one fifth to one half. Analysis indicated, as discussed in more detail later, that tracking errors made only a small contribution to the measured random bomb miss, so that strong correlation could not be expected in any prediction method of this type. In view of these negative results, no effort will be made to describe computational details involved in the various attempted prediction methods.

The fact that the predicted values of random bomb error were in all cases much less than the measured error strengthened the suspicion that sources other than tracking accuracies were responsible for the major portion of the error. Accordingly, the random bombing errors associated with factors other than normal-acceleration tracking performance were estimated, and the resultant error was compared with the measured data of table II. For these calculations, it was assumed that, as indicated by figure 14, the range and deflection components of the random bomb error were normally distributed and were the summation of errors from a number of sources, each statistically independent and normally distributed. Then the usual standard-deviation equation applies, for example:

$$\sigma_x = \sqrt{\sigma_a^2 + \sigma_b^2 + \sigma_c^2}$$

where $\sigma_a, \sigma_b, \sigma_c$ are the standard deviations of the bomb error due to each source a,b,c. Sample calculations for range error sources other than display tracking are summarized in the following table:

Estimate of bomb range errors

Error source	Assumed σ of error source variations	Bomb range error per unit source error		σ of bomb error, ft	
		Loft	O/S	Loft	O/S
Initiation time	0.1 sec	750 ft/sec	750 ft/sec	75	75
Release time	0.02 sec	270 ft/sec	2810 ft/sec	5	56
Wind	1 knot	59 ft/knot	79 ft/knot	59	79
Airspeed	3 knots	54 ft/knot	34 ft/knot	162	102
Bomb dispersion	5 mils (0.287°)	25 ft/deg	220 ft/deg	7	63
		$\Sigma\sigma^2$		34,424	29,375
		Resultant σ, ft		185	171

The error sources listed are those that came readily to mind and which had an appreciable effect on bomb range error. Then the assumed standard deviation σ for each error source was based on experience gained in the present bomb-drop test and on available LAB data.

1. Initiation time: This error arises from the inability of the pilot to begin the maneuver at the exact instant the airplane passes over the selected initiation point.

2. Release time: This error is attributable to variations in release times from the correct value due to slight resolution errors in the bomb-release gyro and associated mechanisms.

3. Wind: Wind error refers to variations from run to run in the range component of the prevailing average wind.

4. Airspeed: The errors in airspeed represent deviations from the average at the instant of release.

5. Bomb dispersion: This error is caused by individual bomb characteristics and is expressed in terms of bomb flight-path angle after release.

The assumed standard deviations for initiation time and airspeed were estimated from data obtained during the present investigation, while the remaining items were estimated from general experience. High precision is not claimed for these estimates but they are believed to be conservative and reasonable. The bomb range error per unit error for each source was derived from known information about the selected airplane maneuver and from practice bomb-trajectory data obtained through Squadron VX-5. The σ of the bomb range error is, of course, the product of this error ratio and the associated assumed σ of the error source. The resultant σ, equal to the square root of the sums of the squares, is the standard deviation of the bomb range error resulting from the combination of these five tabulated error sources. Although the individual error contributions differ between loft and O/S maneuver cases, the resultant σ is about the same, due to compensating effects. Comparison of these resultant σ values with the corresponding σ_x data corrected for gross weight from table II shows that the order of magnitude is about the same for all cases, even though the effects of normal-acceleration tracking errors were not included in the estimation procedure. This result is consistent with the results of the previously described attempts to predict bomb range error from measured normal-acceleration tracking data, a procedure which yielded miss values consistently much smaller than measured. For example, the addition of even the largest predicted σ of 75 feet due to acceleration tracking error to the σ estimated above from other sources gives the following: For loft,

$$\sigma_x = \sqrt{(185)^2 + (75)^2} = 200 \text{ ft}$$

and for O/S,

$$\sigma_x = \sqrt{(171)^2 + (75)^2} = 187 \text{ ft}$$

If the resultant σ_x is considered as a total predicted random bomb range error, it is seen that the net effect of the tracking-error contribution is only 200 - 185 = 15 feet for the loft, or 187 - 171 = 16 feet for O/S. These calculations also help to explain the difficulty experienced in attempting to correlate the predicted bomb miss due to tracking error with the measured misses; under these conditions, only small positive correlation could be expected even with the most favorable practical experiment. Applications of similar procedure to deflection errors lead to results which were qualitatively similar to those above.

Thus it appears that, contrary to original belief, tracking errors are only one of several sizable sources of random bomb miss. Hence, any equipment such as the windshield-display system, which is designed solely to improve tracking performance, cannot be expected to give any striking reduction in random miss. The apparent differences and inconsistencies between the bomb-miss data of table II for the various flight conditions thus may be due primarily to chance flight-to-flight variations in any of several error sources, rather than to significant differences in tracking performance (particularly in view of the small number of runs for some flight conditions).

From the operational standpoint, the importance of random bomb error due to tracking error would be even less than indicated. For example, in predicting the miss-distance statistics of bombs to be dropped in distant territory, allowance must be made not only for the random miss of a group of bombs from an m.p.i., but also for random errors in estimating the m.p.i. itself. These latter errors can arise from continual changes in "system" errors and from errors in predicting winds over a target, a difficult task even in friendly areas. Brief consideration of available data, including that from the present bomb drops, indicates that these errors may well be considerably larger than the random bomb error. In fact, the present data indicate that reduction in such errors in estimating the m.p.i. is of greater practical importance than the reduction of random errors about the m.p.i., such as the relatively small ones associated with the tracking inaccuracies of initial concern in this present study. Further detailed analysis of the relative tracking ability with the two systems was not considered warranted since, in this particular application, the tracking-error contribution to the end result was small.

Equipment Development Flights

As has just been discussed, the windshield display did not give significant improvement from the bomb accuracy standpoint. However, experience with this equipment indicated that equipment employing similar display principles might be profitably applied to other flight problems, particularly where continuous and precise control of the flight path is of greater over-all importance. The following discussion of pilot opinion, tracking performance and experience gained in the development of this equipment may be of value in this connection.

<u>Selection of display sensitivities</u>.- Display sensitivity is the angular displacement of the moving-dot instrument index per unit of error: in the elevation channel, the vertical displacement in milliradians per g unit error; and in the deflection channel, the horizontal displacement in milliradians per degree yaw error or degree roll error. The selection of sensitivity values for use in the final evaluation of practice bomb-miss distances was based on pilots' opinions of the ease of tracking the windshield display and on the acceleration, yaw, and roll errors which should be minimized to insure repeatable maneuvers. In this equipment the sensitivity could be varied over a continuous range from zero to exceedingly high values. Therefore, in initial flights a range of probable useful values was given to the pilot as a general guide for investigation. As flight tests progressed, the pilot narrowed these initial values to a range of useful sensitivities. Following these tests, check flights by other pilots were made to verify these settings. The sensitivities determined during these tests are as follows:

Pitch sensitivity . . . 44 milliradians per g unit error
Yaw sensitivity . . . . 17 milliradians per deg yaw error
Roll sensitivity . . . 7 milliradians per deg roll error

In selecting the display sensitivities for use in later bomb-drop tests, the maximum usable values were limited by excessive high-frequency dot motion in rough air, which made it difficult for the pilot to detect the desired flight indications. Lower settings, of course, reduce dot excursions due to rough air and improve the tracking in terms of dot displacement. In the extreme, apparent tracking errors would approach zero as the sensitivity approached zero, but the associated normal acceleration and roll-yaw errors would be very large. Extensive study of the variation of the actual tracking errors with sensitivity was beyond the scope of the present study, but it appeared that they could not be reduced significantly by changing sensitivities from the selected values which are the maximum usable under rough-air conditions. Filters probably could be designed for the mirror servo loop which would reduce the high-frequency dot motion due to rough air without appreciable attenuation of tracking-control dot motions, thus permitting the use of higher sensitivities. Effects of simple adjustments were considered briefly, but no time was available for extensive development.

It is interesting to interpret the selected sensitivities in terms of thresholds detected by the pilots. The diameter of the moving dot is about 2 milliradians, and a tracking error of one dot diameter was readily apparent to the pilot. The highly sensitive nature of this display is apparent when this dot-width error is converted into the flight quantities of 0.046g acceleration error, 0.12° yaw error, and 0.28° roll error.

The ratio of 0.28° roll to 0.12° yaw is of the same order as the roll-yaw signal ratio of 3 to 1 used in the standard system. If the steady-state approximation is made so that the rate of yaw correction is proportional to bank angle, the addition of the roll-angle term to the azimuth dot motion can be thought of as providing the pilot with a lead term. This has an effect similar to that of elevating a fixed gunsight above the airplane reference axis; here, banking motions not only are a measure of the eventual azimuth correction rate, but also provide an apparent azimuth tracking correction proportional to the bank angle. Moderate elevation of a gunsight (which gives equivalent roll-yaw ratios of the order used with the LAB system) has been found generally beneficial to tracking.

Modification of acceleration program.- The specified LAB maneuver calls for a smooth pull-up entry from 1g to 4g in 2 seconds. The original windshield-display system cam profile is shown in figure 15(a). The smooth asymmetrical S curve used for the entry portion was selected as a reasonable approximation to the normal-acceleration pattern as measured in abrupt pull-ups made using normal control techniques. Difficulty in following this abrupt command was experienced during initial flights. In the hope of facilitating closer and more consistent tracking, a cam with a modified entry profile was constructed in which the S shaped entry portion was lengthened to 2.5 seconds (fig. 15(b)).

The final portion or tail of the cam was originally tapered (fig. 15(a)) to correspond to the drop-off in maximum usable total lift associated with the estimated sizable reduction in indicated airspeed during the latter portion of the maneuver. On the basis of early experience with the airplane, the pilots believed it would be possible to hold 4g throughout the 180° pitch maneuver. Accordingly, the tail portion of the cam with the modified entry profile was left constant at 4g (fig. 15(b)).

Subsequent flight tests with the modified cam showed that, contrary to expectations, the pilots preferred the 2-second cam and (after practice) were able to fly smoother and more repeatable maneuvers with the original abrupt entry. Apparently the control motions and associated airplane response with the original cam corresponded more closely to those used naturally by a pilot for any abrupt pull-up. In addition, the tapering of the final portion of the g command was found to be essential, as it was not possible to hold the constant 4g called for by the modified cam. In fact, the shape of the original cam was found to be just inside the airplane buffet boundary. For these reasons, the original cam profile (fig. 15(a)) was selected for use in all subsequent bomb-drop tests.

Measured tracking performance.- The flight-test program of the windshield-display system, including the practice bomb drops, encompassed over 60 flights and more than 600 pull-up maneuvers. From the numerous records obtained, several interesting trends were noticed in the measured tracking, particularly in pitch - that is, the nature and magnitude of the errors between actual and desired acceleration. Typical variations in normal-acceleration tracking performance associated with various pilot techniques, system configurations, and atmospheric conditions are shown in figure 16. With the standard system (fig. 16(a)), the measured acceleration was usually quite smooth but was often less than the desired value in the middle portion of the run. It is believed that this difference between desired and actual acceleration is due not only to the coarseness of the acceleration error indication, but also to difficulty in maintaining an accurate calibration of the acceleration error channel. For the windshield display with the acceleration error integrator out, figure 16(b), the normal acceleration patterns were characterized by a short lag behind the command during the entry period. During the middle portion the long-term acceleration errors were held quite small, but at the expense of increased higher frequency deviations, an effect probably associated with the pilots' efforts to track closely when using this highly sensitive display. Addition of the integrated-error signal (fig. 16(c)) resulted in a tendency to overshoot the specified 4g in the maneuver entry, an effect normally associated with the addition of a lag term in a closed-loop system. It did not result in the hoped-for reduction of bias errors, which in initial tests were high with the integrator-out system. In fact, the tracking errors with the integrator in appeared to be larger and slightly more oscillatory than with the integrator out, and the pilots reported somewhat more difficulty in tracking. Once this tendency toward acceleration bias errors was called to their attention, and as they gained flight experience, they were able to hold it to satisfactorily low levels without the integrator. Consequently, extensive development of the integrated-error concept was abandoned.

The effect of rough air on the windshield-display-system tracking is shown in figure 16(d) for the integrator-out case. A lag in initiating the maneuver is apparent; this effect is associated primarily with the pilot's difficulty in detecting the acceleration command in the midst of sizable random normal accelerations and dot motions caused by the rough air. It is seen that the pilot applied acceleration rapidly to reach the command, but had subsequent difficulty in stabilizing about 4g. The normal-acceleration errors were reduced later in the run since the air smoothed out with increasing altitude, and the problem became one of 4g tracking. Figure 16(e) shows an interesting effect that was sometimes observed when the pilot attempted to track the moving dot very tightly. Poorly damped oscillations of about 1 cycle per second are readily apparent. This oscillation seemed to be associated with a combination of the airplane longitudinal short-period oscillation of about the same frequency and the pilot's difficulty in controlling at this high frequency, particularly through an airplane control system with dynamic imperfections. As discussed previously, the pilots had difficulty in following the initial acceleration rise when it was spread out over a 2-1/2-second period (fig. 15(b)). The example acceleration time history of figure 16(f) shows the typical "hitch" in the acceleration entry curve due apparently to his fear of overshooting this more gradual acceleration command.

The normal-acceleration tracking performance with the windshield-display system as finally used in the practice bomb drops is summarized in figure 17. These data, in the form of time histories of average normal accelerations and root-mean-square deviations from this mean value, are based on the data from only the 14 bomb-drop flights. Here the system configuration was held constant and only two pilots who used similar tracking techniques were involved. The air roughness varies from slight to moderate for the flights in this summary. It is seen that for both integrator in and out the curves are much the same, except for a slightly greater tendency with integrator in to overshoot the desired 4g at about 3 seconds.

The inability to keep up with the initial command is reflected in peak acceleration errors of about -0.4g to -0.5g at 1.5 seconds. The error is first reduced to zero at 2-1/2 seconds. Then as time increases toward 10 seconds there is a trend toward increasingly negative error. As seen from figure 17(a), at 10 seconds the acceleration command starts to reduce, resulting in a brief period of positive error around 12 seconds until the pilot readjusts.

The standard deviation σ of the error from the mean value is seen to range from around ±0.3g near the start of the run to as low as ±0.1g later in the run. The values of σ with integrator in are slightly greater than with integrator out, reflecting the pilots' opinion that the tracking was easier with the integrator out. It might be noted that the σ boundaries of normal acceleration can be interpreted as enclosing 68.3 percent of the test points, indicative of the repeatability from run to run.

The roll-yaw tracking errors were generally small (less than ±1.0°) and did not appear to be strongly influenced by display or flight conditions. One notable exception was the effect of airplane yaw-damper operation. Example yaw-error time histories shown in figure 18 illustrate the small virtually undamped yawing oscillations which were evident with the yaw damper inoperative, particularly in rough air. In all cases these roll-yaw tracking errors appeared to have little effect on random bomb errors.

Pilot opinions.- During the course of the flight program, an effort was made to obtain pilot comments on the advantages, deficiencies, and possible modifications of the windshield-display system. In addition to the present LAB maneuver, comments relating to other possible applications were also of interest. After completion of all flight tests by VX-5 pilots, two local evaluation flights were made by Ames pilots. While they did not have any previous LAB experience, both had wide experience in tracking research studies including the target-simulator program (ref. 1). Low-altitude bombing maneuvers were performed on both the standard and windshield-display systems for pilot comment only, based on their experience with similar displays at the Laboratory. The following discussion is a consensus of all VX-5 and Ames pilots involved in the test program.

The pilots appreciated the large and sensitive nature of the moving-dot display, and considered it a natural, easily interpreted way of combining pitch and yaw flight information. Since these tests were performed over a familiar and unobstructed path, the pilots felt safe in concentrating on the dot-tracking problem with little reference to the outside world. However, when the pilot attempts this half loop in combat over unfamiliar terrain, the ease with which he can monitor the surroundings and transfer from instrument to visual orientation might be an important advantage of the windshield display. The pilots also felt that this visual flight monitoring feature might be very useful in other possible applications, such as landing-approach instrumentation where a difficult transition from instrument to visual orientation is required. The flexibility of the continuous programming principle enhances the application to radically different and more difficult flight maneuvers.

The pilots offered numerous suggestions for modifications to the windshield display itself, but these were not considered essential to the present exploratory investigation. The displaying on the windshield of airspeed or airspeed error was considered a desirable addition to reduce the distraction of reading a separate standard airspeed indicator. There were several widely differing suggestions dealing with the addition of roll-orientation information, these ranging from a simple vertical reference line fixed in the airplane to "wings" on the moving dot; the latter would not only provide a bank reference but would permit programming of the roll-out required for recovery from the LAB maneuver. The replacement of the fixed dot with a small circle was considered desirable to improve definition. Increased display brilliance and heavier sunlight filtering were considered essential for daylight operational use. These improvements and changes to the display probably could be accomplished more readily through the use of a cathode-ray tube of the projection type or the flat-screen type, rather than the electro-mechanical device used in the present windshield-display system.

CONCLUDING REMARKS

Low-altitude bombing tests made in an F9F-8 airplane with the standard Navy cross-pointer indicator and with the tracking-type windshield display described herein showed slight differences in practice-bomb random miss distances. However, these did not appear large enough to affect appreciably the bomb miss on a tactical mission. For example, in high-angle (120°) "over-the-shoulder" releases the mean radial error was reduced from 315 feet for the standard system to 269 feet for the windshield-display system. The standard deviations of the range and deflection components were 197 feet and 324 feet, respectively, for the standard system, and 130 feet and 289 feet for the windshield-display system. However, in medium-angle (41°) "loft" releases the mean radial error increased slightly from 201 feet for the standard system to 230 feet for the windshield-display system.

There were noticeable differences in pilot techniques and tracking performance among the many pilots who performed preliminary flights. However, the observed differences in bomb miss were small for the two project pilots, and their data were grouped together for analysis. Addition of an error-integral signal in the normal-acceleration channel of the windshield display resulted in moderate but inconsistent differences in measured bomb-miss distances. For simplicity these data have been grouped to facilitate the numerical comparisons above. With both types of low-altitude bombing (LAB) systems a progressive change in bomb miss from run to run was observed. This effect is associated with changes in the airplane angle of attack at release due to gross weight changes with fuel consumption. Although accurate fuel consumption data were not available, approximate corrections were made to the present data, and it appears that this factor should be considered in tactical applications.

There were strong indications that errors in instrument tracking accounted for only a small part of the random bomb miss. In turn, it appears that these measured random miss distances represent a lesser part of the over-all bomb miss to be expected on a tactical mission. This fact suggests that attention should be concentrated on reduction of LAB error sources other than tracking - for example, the prediction and compensation for wind.

Despite the absence of appreciable improvement in bombing accuracy, the windshield display was highly regarded by the pilots. While there were suggestions for minor improvements, the pilots generally found the windshield display a natural one, easy to learn and to fly with confidence. These favorable opinions leave open the possibility that the windshield-display concept might be applied fruitfully to other instrument flight problems in which continuous and precise control of the flight path are of greater over-all importance.

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
Moffett Field, Calif., Sept. 10, 1956

APPENDIX

DESCRIPTION OF COMPONENTS

Figure 5 is a block diagram of the windshield-display system. The elevation and azimuth drive motors, microsyn pickoffs, and the mirror gimbal are all integral components of the modified A-1 sight head shown in figure 4. Here the path of the light beam to the fixed and moving mirror assemblies is illustrated. The fixed mirror is a specially treated piece of glass added to the sight head to create the fixed-dot image. The moving mirror gimbal is positioned by direct-current motors which are driven by a conventional servo amplifier, the microsyns providing the alternating-current feedback signals. A 400-cycles-per-second signal system is used throughout to permit stable amplification without excessive complication. When direct current is necessary, 400-cps chopper demodulators are utilized. A separate 28-volt d-c to 110-volt a-c 400 cps inverter is employed as a primary power source for the entire system for complete isolation from any aircraft 400-cps sources.

The error signals are derived at the summing junctions of the error-signal amplifiers in each channel. In the elevation channel the amplified output of a Schaevitz linear accelerometer, oriented to measure the aircraft's normal-acceleration component (A_Z), is compared with the output of a linear differential transformer (linearsyn) pickoff which senses the contour of the program cam. The programmer unit (fig. 3) contains the constant-speed motor, acceleration-program cam, the linearsyn pickoff, and the sequencing and program reset relays and switches. The roll- and yaw-axis gimbal pickoffs are wire-wound potentiometers and, for proper operation in this system, were excited by a 400-cps voltage balanced against ground. The roll and yaw sensitivity controls were located in the pilot's control panel until the sensitivity tests were completed, when they were replaced with fixed attenuators. The error-signal amplifiers are of conventional design and are virtually identical except for the pilot's acceleration error control in the elevation channel. This control was omitted from the azimuth channel because the roll and yaw sensitivity controls had the same effect. The integrator was of the simplest variety, employing an RC network with a time constant of 50 seconds, which permits a sufficiently accurate integration to the time of release which had a maximum value of about 13 to 14 seconds. A switch to select integrator operation and a sensitivity potentiometer are provided for the pilot. It is to be borne in mind that in the construction of this equipment no attempt to miniaturize or optimize the various components was made. Off-the-shelf components available at the Laboratory were used whenever possible to minimize development time.

REFERENCES

1. Doolin, Brian F., Smith, G. Allan, and Drinkwater, Fred J., III: An Air-Borne Target Simulator for Use in Optical-Sight Tracking Studies. NACA RM A55F20, 1955.

2. Anon.: Handbook and Service Instructions, Aero. 18A Armament Control System. NavAer 11-5MD-501.

TABLE I.- INDIVIDUAL BOMB-DROP DATA

Flight no.	Direction	Measured miss, ft: Range	Measured miss, ft: Deflection	Random error, ft: Range	Random error, ft: Range corrected for gross weight error	Random error, ft: Deflection	Random error, ft: Radial corrected for gross weight error
(a) Flight condition: O/S integrator out							
1	S	58	1229	509	279	259	380
	S	-656	1082	-206	-206	112	234
	N	493	-80	142	27	-127	129
	S	-752	600	-302	-72	-370	376
	N	210	173	-141	-27	126	128
2	S	-462	158	62	-168	34	171
	N	-421	-600	254	24	41	47
	S	-322	-31	202	202	-155	254
	N	-828	-494	-153	-153	147	212
	S	-787	246	-263	-33	122	126
	N	-776	-828	-101	129	-187	227
(b) Flight condition: O/S integrator in							
3	S	1140	970	375	101	208	231
	N	-418	915	141	-133	445	464
	S	811	832	46	46	70	84
	N	-460	577	99	99	107	146
	S	345	484	420	-146	-278	314
	N	-800	-83	-241	33	-553	554
4	S	810	1600	25	-112	200	229
	N	-560	-79	298	24	-356	357
	S	760	1200	-25	112	-200	229
	N	-1082	422	-224	-224	145	267
	N	-932	488	-74	200	211	291
5	S	1000	1400	230	-44	-23	50
	N	-155	15	347	73	584	589
	N	-390	-863	112	112	-294	315
	S	540	1445	-230	44	22	49
	N	-962	-858	-460	-186	-289	344
6	S	273	620	288	-96	-230	249
	S	212	608	227	117	-242	269
	S	-189	1610	-174	-147	760	774
	S	-146	1065	-131	33	215	218
	S	-225	348	-210	91	-502	510
7	N	-2016	-682	103	-171	74	186
	S	2245	31	90	-47	-530	533
	N	-2071	-469	48	48	287	291
	S	2066	1091	-89	47	530	532
	N	-2269	-1118	-150	124	-362	383
8	S	-36	0	380	106	-83	135
	S	-302	331	114	-23	248	249
	S	-266	102	150	150	19	151
	S	-718	-270	-302	-169	-353	391
	S	-758	254	-342	-68	171	184
9	S	-386	193	396	122	-65	138
	S	-755	162	27	-110	-96	146
	S	-772	498	10	10	240	240
	S	-868	103	-86	-51	-155	163
	S	-1131	335	-349	-75	77	107

TABLE I.- INDIVIDUAL BOMB-DROP DATA - Continued

(c) Flight condition: loft integrator out							
Flight no.	Direction	Measured miss, ft		Random error, ft			
		Range	Deflection	Range	Range corrected for gross weight error	Deflection	Radial corrected for gross weight error
10	S	680	175	-140	35	57	67
	N	1161	795	-335	-160	310	349
	S	822	82	2	2	-36	36
	N	1472	527	-24	-24	42	47
	S	958	98	138	-37	-20	41
	N	1854	133	358	183	-352	396
11	S	-827	98	-373	-198	43	203
	N	-792	8	-512	-337	-213	398
	S	-361	-186	93	93	-241	258
	N	-353	512	-73	-73	291	300
	S	-173	253	281	106	198	224
	N	304	143	584	409	-78	416
(d) Flight condition: loft integrator in							
12	S	-42	450	6	6	321	321
	S	-40	-75	8	8	-204	204
	S	-62	13	-14	-14	-116	117
13	N	209	248	-120	-120	-39	382
	S	-404	-4	363	363	-118	383
	N	208	521	-121	-121	234	126
	S	-1131	232	-364	-364	118	263
	N	569	93	240	240	-194	309
14	S	-959	267	-153	-153	-45	159
	S	-772	227	34	34	-85	92
	S	-646	72	160	160	-240	288
	S	-881	532	-75	-75	220	232
	S	-770	462	36	36	150	154

TABLE I.- INDIVIDUAL BOMB-DROP DATA - Concluded

Flight no.	Direction	Measured miss, ft		Random error, ft			
		Range	Deflection	Range	Range corrected for gross weight error	Deflection	Radial corrected for gross weight error
(e) Flight condition: loft standard system							
15	N	-527	165	152	152	54	161
	S	-731	536	-248	-248	7	248
	N	-881	205	-202	-202	14	202
	S	-235	522	248	248	-7	248
	N	-630	287	49	49	-68	83
16	S	-948	-262	-160	-160	14	161
	N	-823	-137	-123	-123	-132	180
	S	-658	-204	130	130	72	149
	N	-728	-163	-28	-28	-158	160
	S	-757	-361	31	31	-85	286
	N	-550	286	150	150	291	327
17	N	-254	105	24	24	-195	196
	N	-301	495	-23	-23	-195	139
18	S	-276	53	-168	-168	-12	168
	N	60	-400	63	63	-220	229
	S	-157	-179	-49	-49	-244	249
	N	72	-92	75	75	88	116
	S	110	322	218	218	257	337
	N	-140	-47	-137	-137	133	191
(f) Flight condition: 0/8 standard system							
19	S	960	130	-74	-225	-64	233
	N	918	212	355	204	-431	476
	S	1322	155	288	288	-39	290
	N	459	992	-104	-104	349	364
	S	817	298	-217	-66	104	123
	N	313	725	-254	-103	82	131
20	S	-783	-153	293	142	-194	240
	N	1145	569	287	136	236	272
	S	-816	178	260	260	137	293
	N	760	-458	-98	-98	-792	798
	S	-1629	97	-553	-402	56	405
	N	669	890	-189	-38	556	557
21	S	845	-950	367	216	35	218
	N	-100	-1358	130	-21	-63	66
	S	728	-918	250	250	67	258
	N	-67	-1457	163	160	-162	227
	S	-139	-1086	-617	-466	-101	476
	N	-522	-1071	-292	-141	224	264
22	S	2241	4	202	51	-69	86
	N	-995	-282	478	327	239	405
	S	2013	158	-26	-26	85	89
	N	-1508	-1200	-35	-35	-679	679
	S	1862	58	-177	-26	-15	30
	N	-1915	-82	-442	-291	439	526
23	S	839	540	276	125	172	212
	N	-28	160	442	291	248	382
	S	555	455	-8	-8	87	89
	N	-472	-400	-2	-2	-312	312
	S	294	109	-269	-118	-295	317
	N	-910	-25	-440	-289	63	295
24	S	700	379	447	296	315	432
	N	498	402	224	73	423	429
	S	330	-729	77	77	-793	251
	N	23	-171	-251	-251	-150	[illegible]
	S	-272	541	-525	-374	477	606
	N	300	-294	26	177	-273	325
25	S	227	-110	47	-28	-433	433
	N	-38	545	247	96	25	31
	N	-298	825	-13	-13	305	305
	S	134	756	-46	30	433	434
	N	-518	190	-233	-82	-330	340

TABLE II.- SUMMARY OF RANDOM ERROR ANALYSIS

Flight condition: Maneuver	Flight condition: Display system		Number of runs	σ_y deflection component, ft	σ_x range component, ft	σ_x component corrected for gross weight error, ft	Mean radial error, ft	Mean radial error corrected for gross weight error, ft
O/S	Windshield	Integrator in	36	313	233	111	351	288
		Integrator out	11	202	244	147	266	208
		Combined	47	289	239	130	332	269
	Standard		41	324	287	197	392	317
Loft	Windshield	Integrator in	13	179	177	177	233	233
		Integrator out	12	196	305	184	349	228
		Combined	25	188	249	181	288	230
	Standard		19	149	141	141	201	201

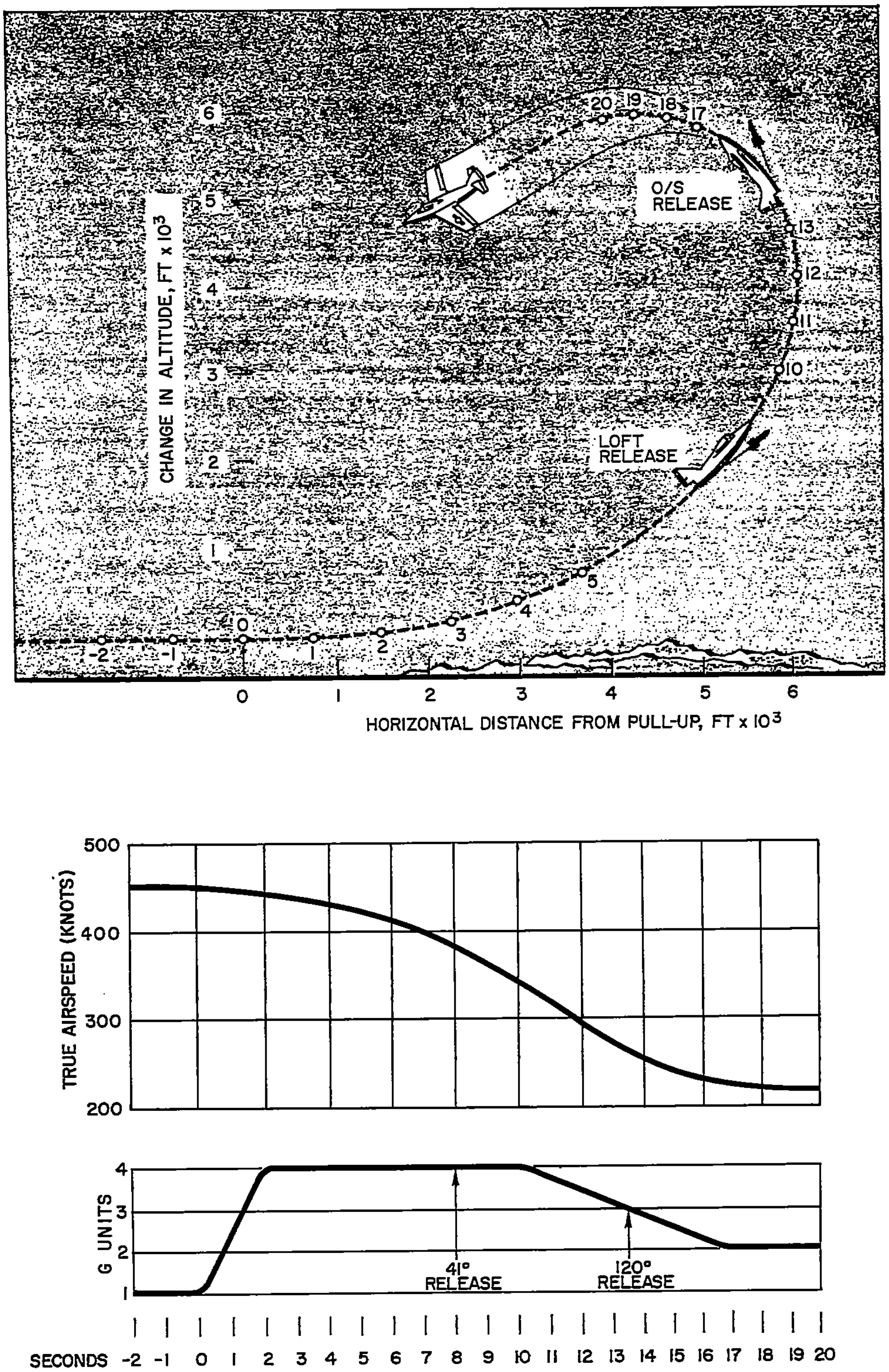
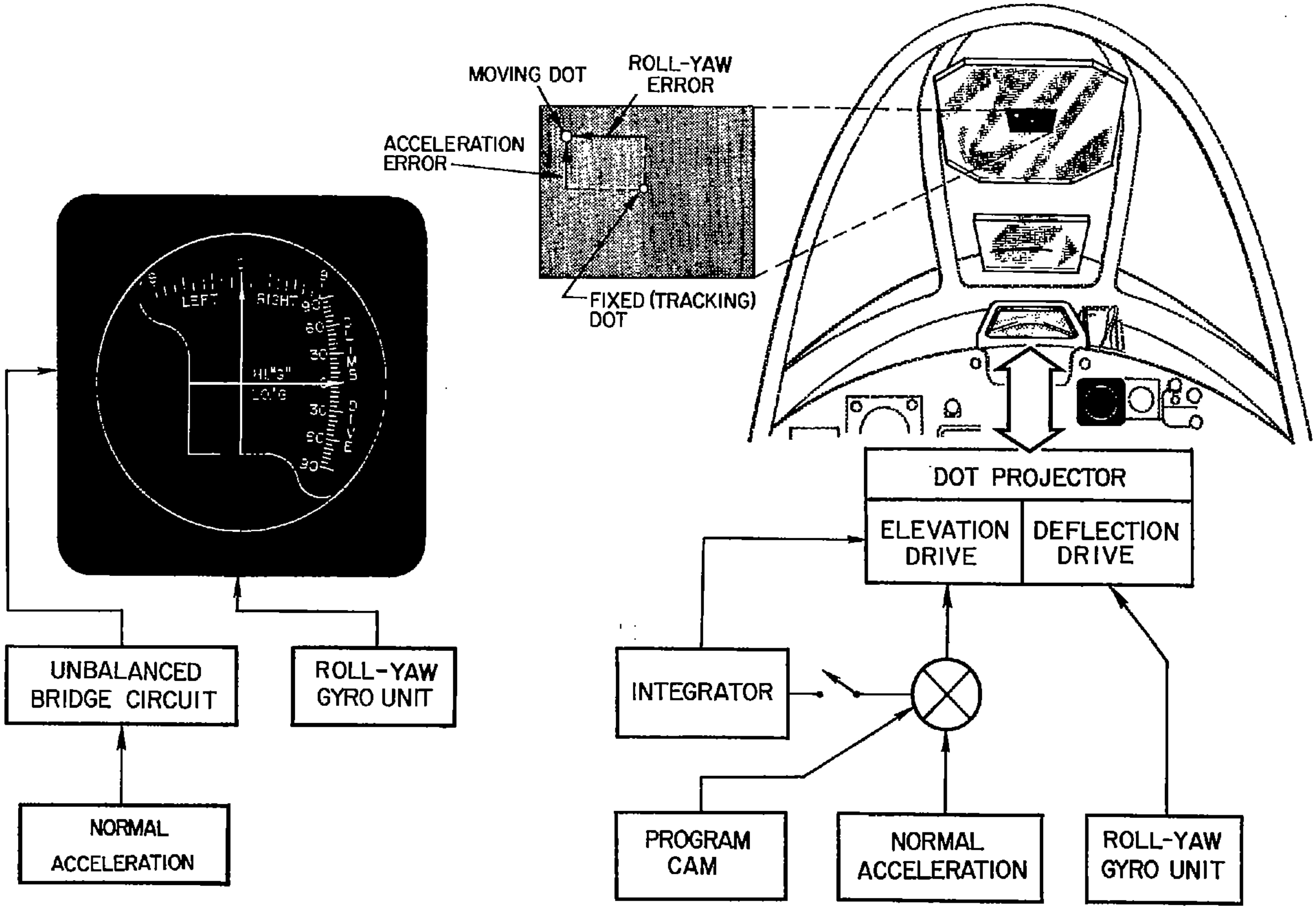


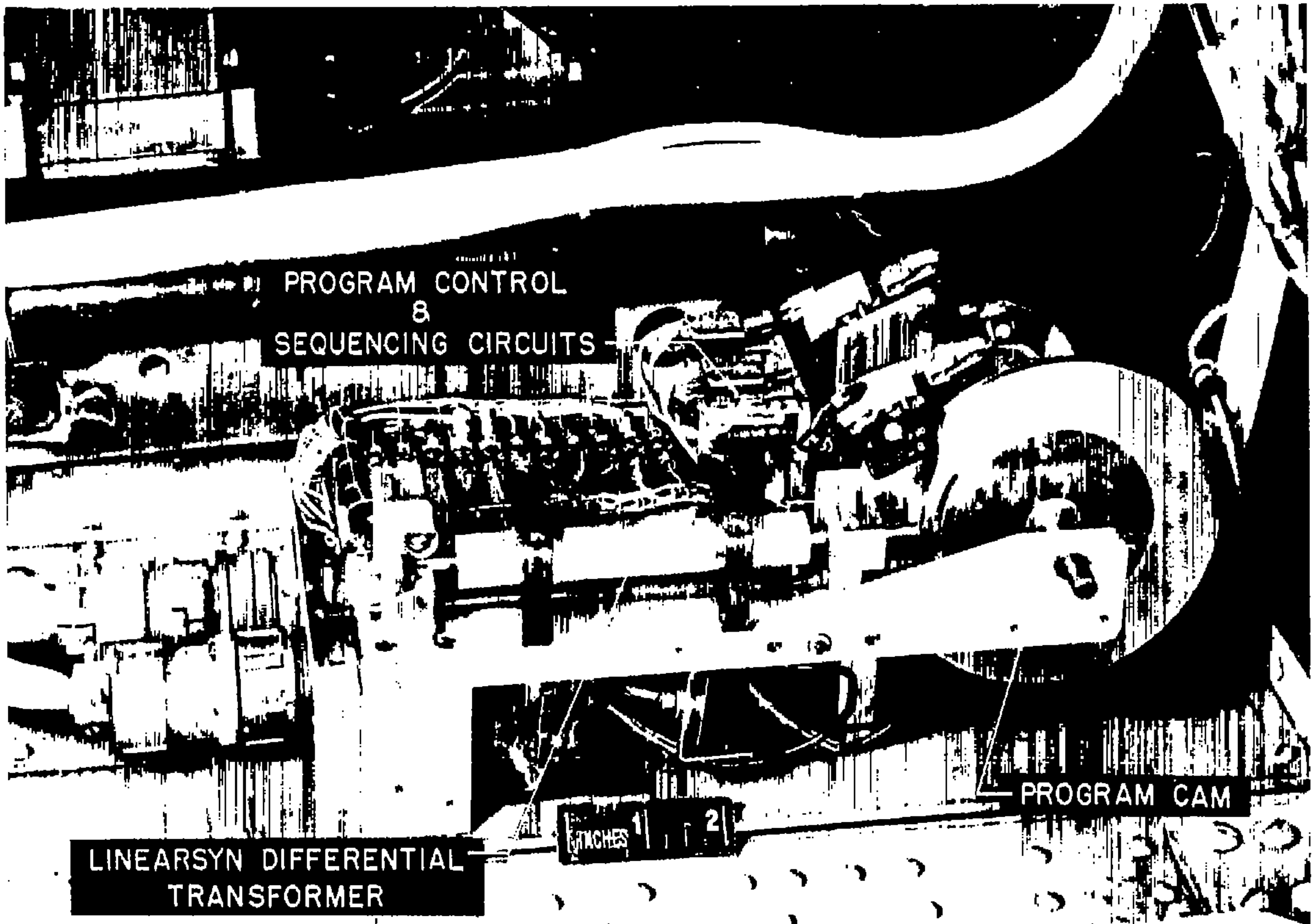
Figure 1.- An idealized low-altitude bombing maneuver.



(a) Standard system.

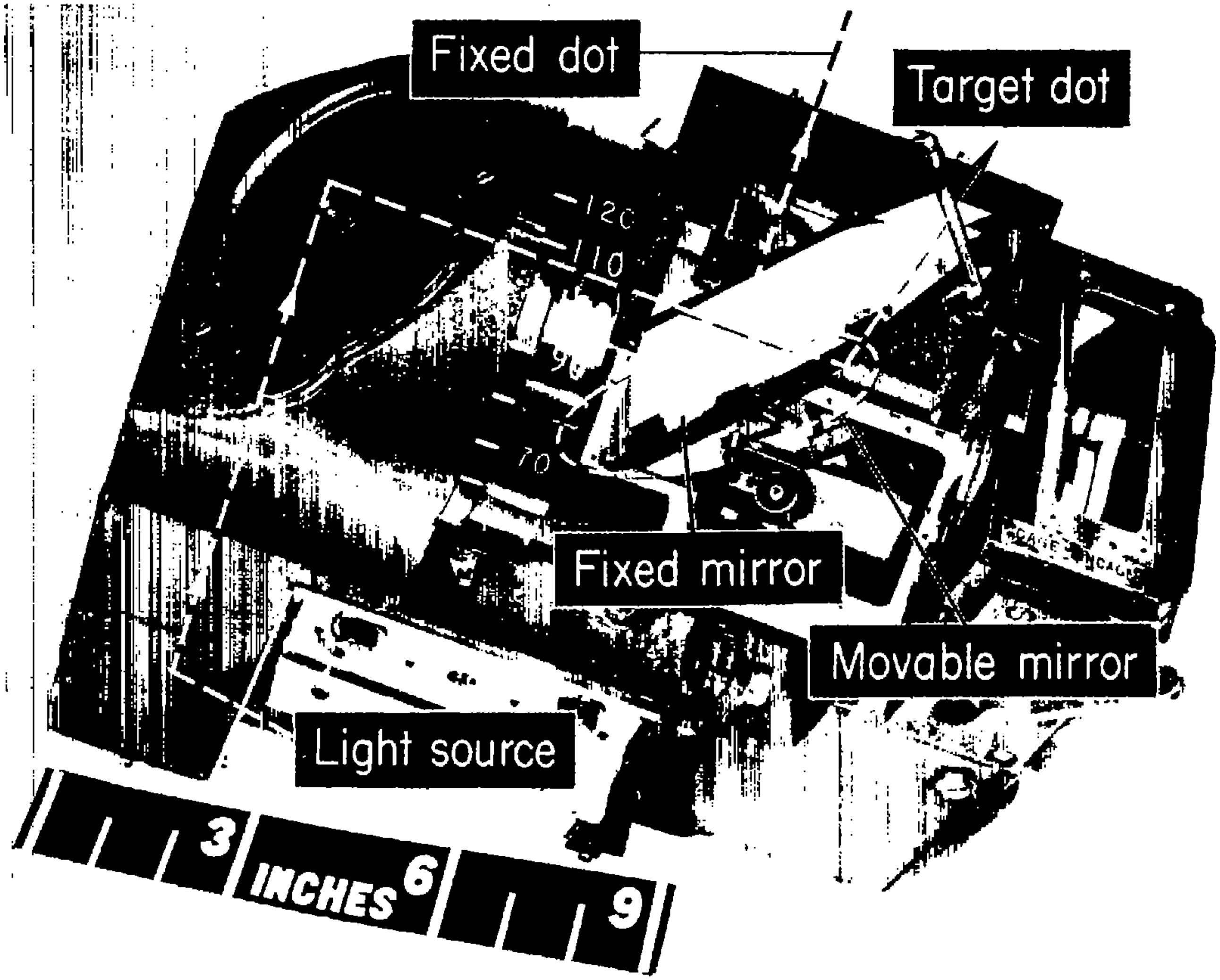
(b) Windshield-display system.

Figure 2.- Diagrams of the two low-altitude bombing systems.



A-20344.2

Figure 3.- General view of the acceleration programmer.



A-19436

Figure 4.- Cutaway view of the A-1 sight-head optical projector.

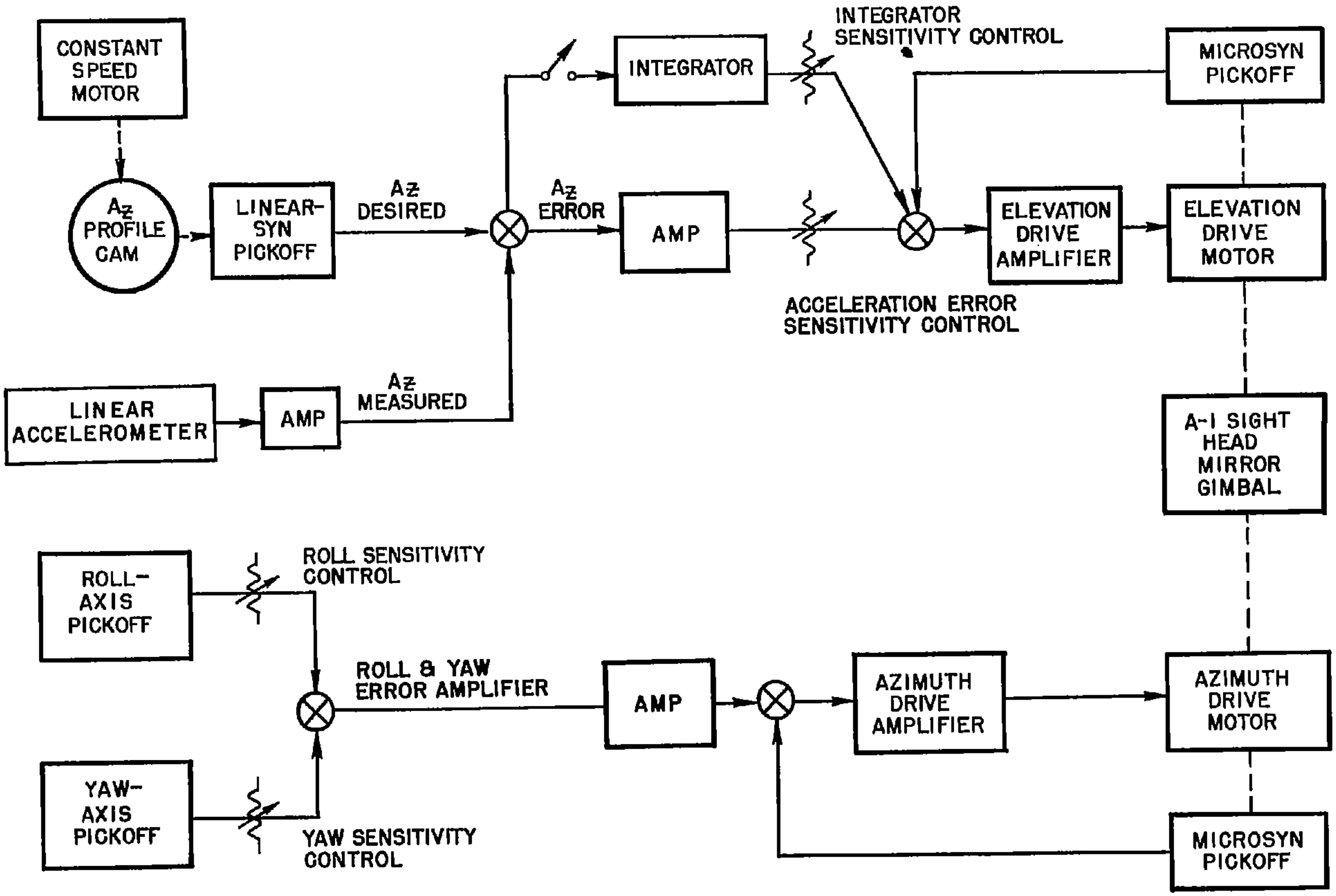


Figure 5.- Block diagram of the windshield-display low-altitude bombing system.

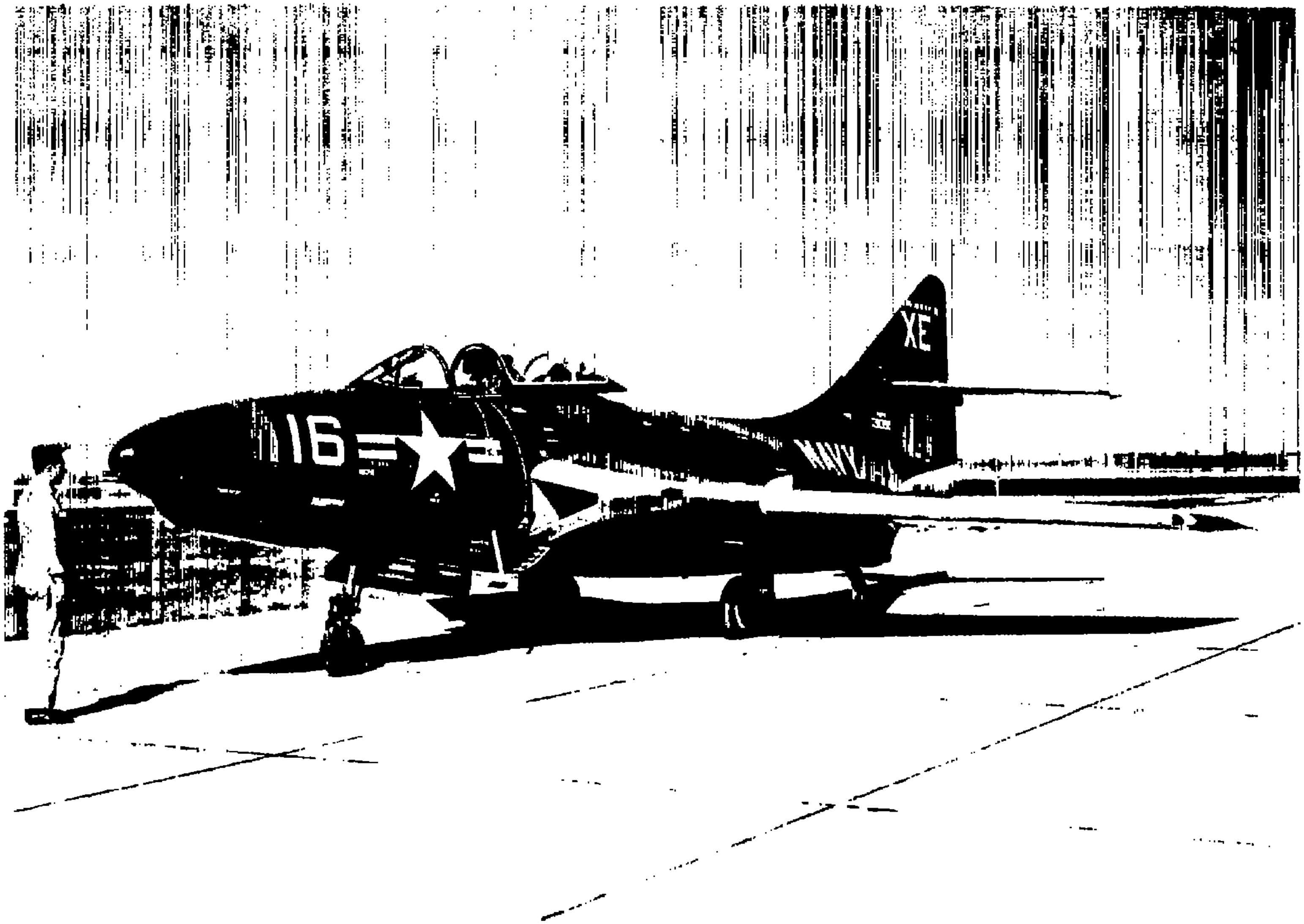


Figure 6.- General view of the test airplane, a Grumman F9F-8, BuAer No. 131086.

A-20186

CONFIDENTIAL

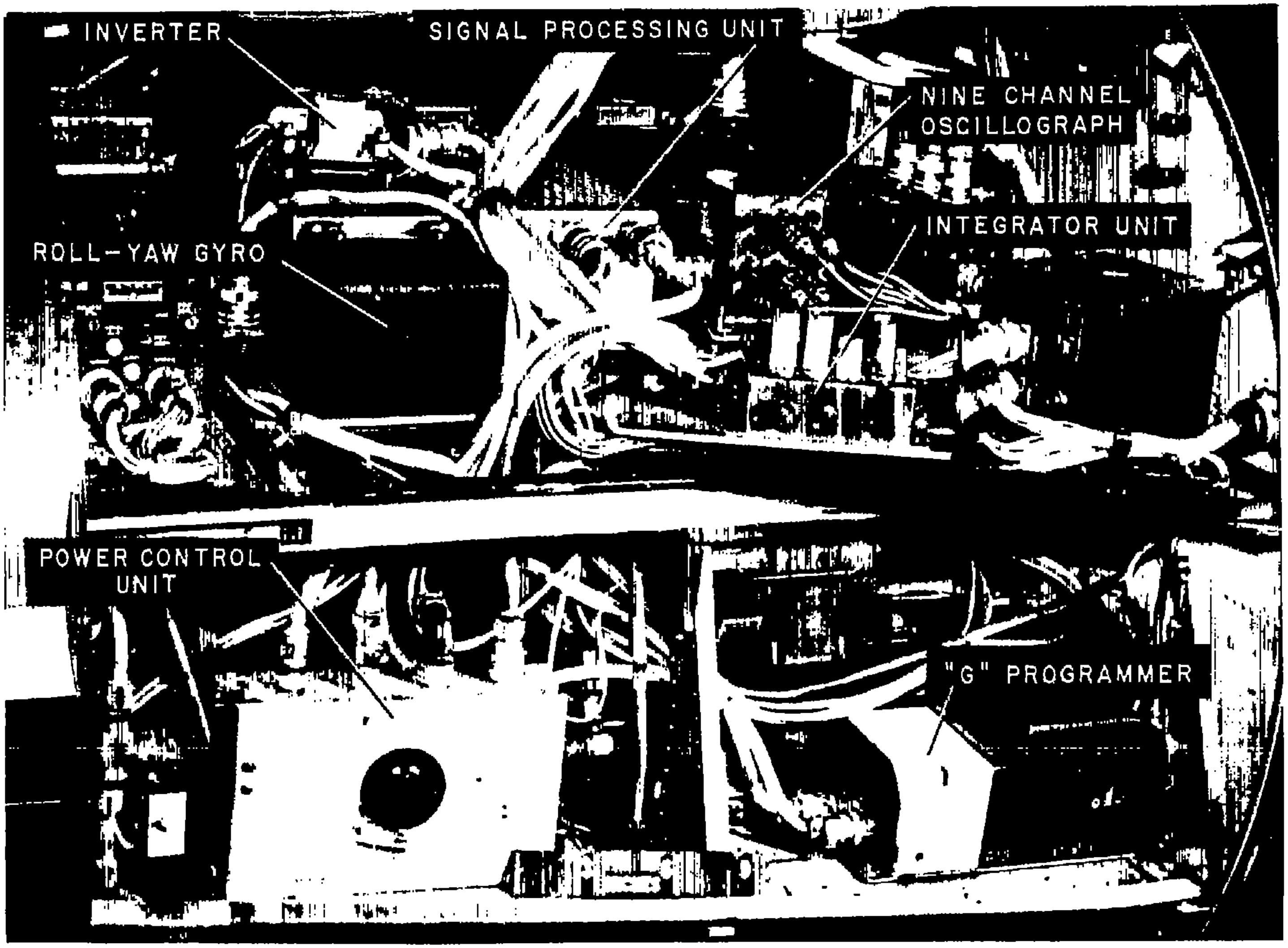


Figure 7.- General view of left-hand side of the test-airplane nose compartment showing details of equipment installation.

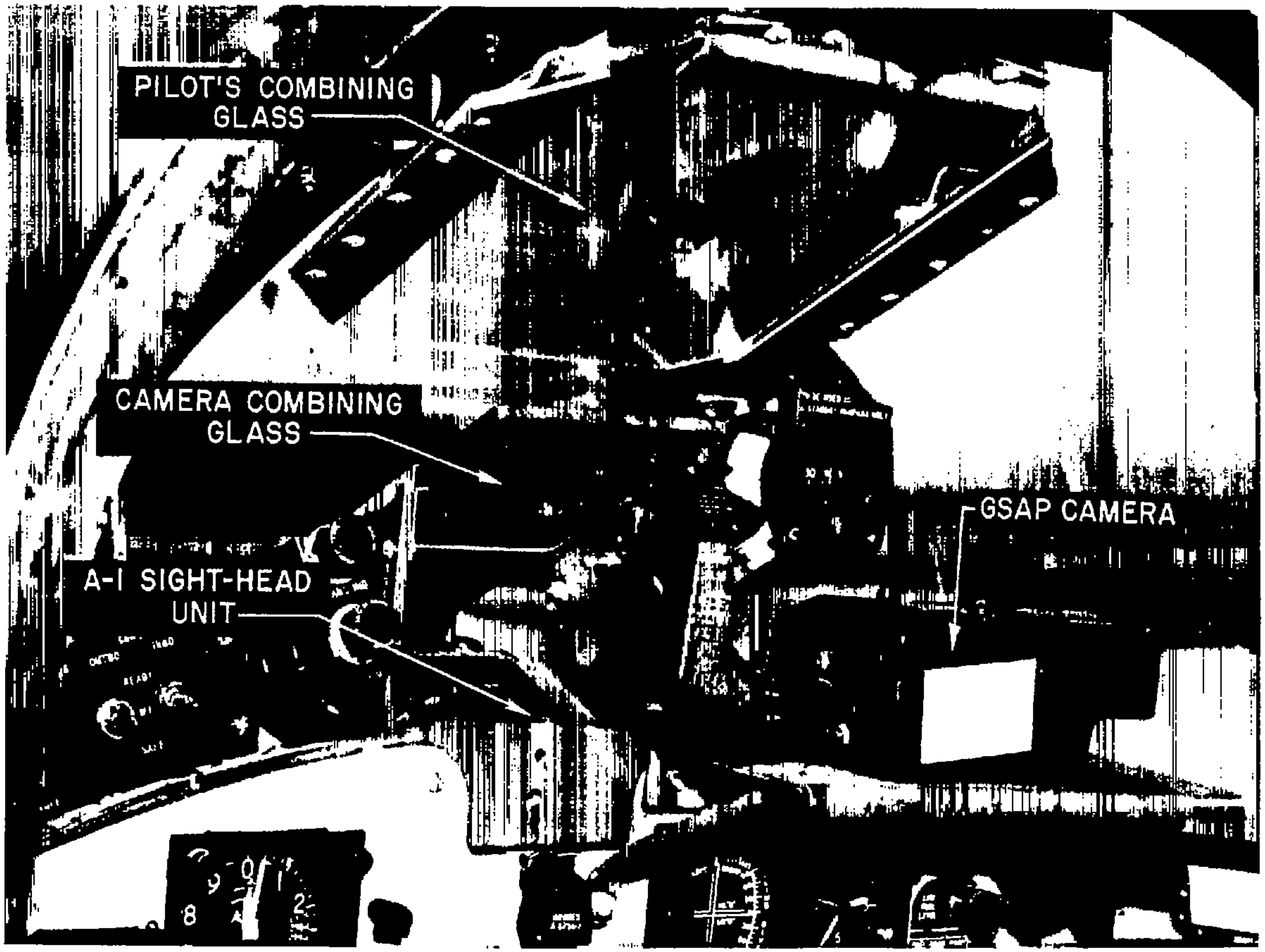


Figure 8.- Close-up view of the cockpit sight head and camera installation. A-20640.3

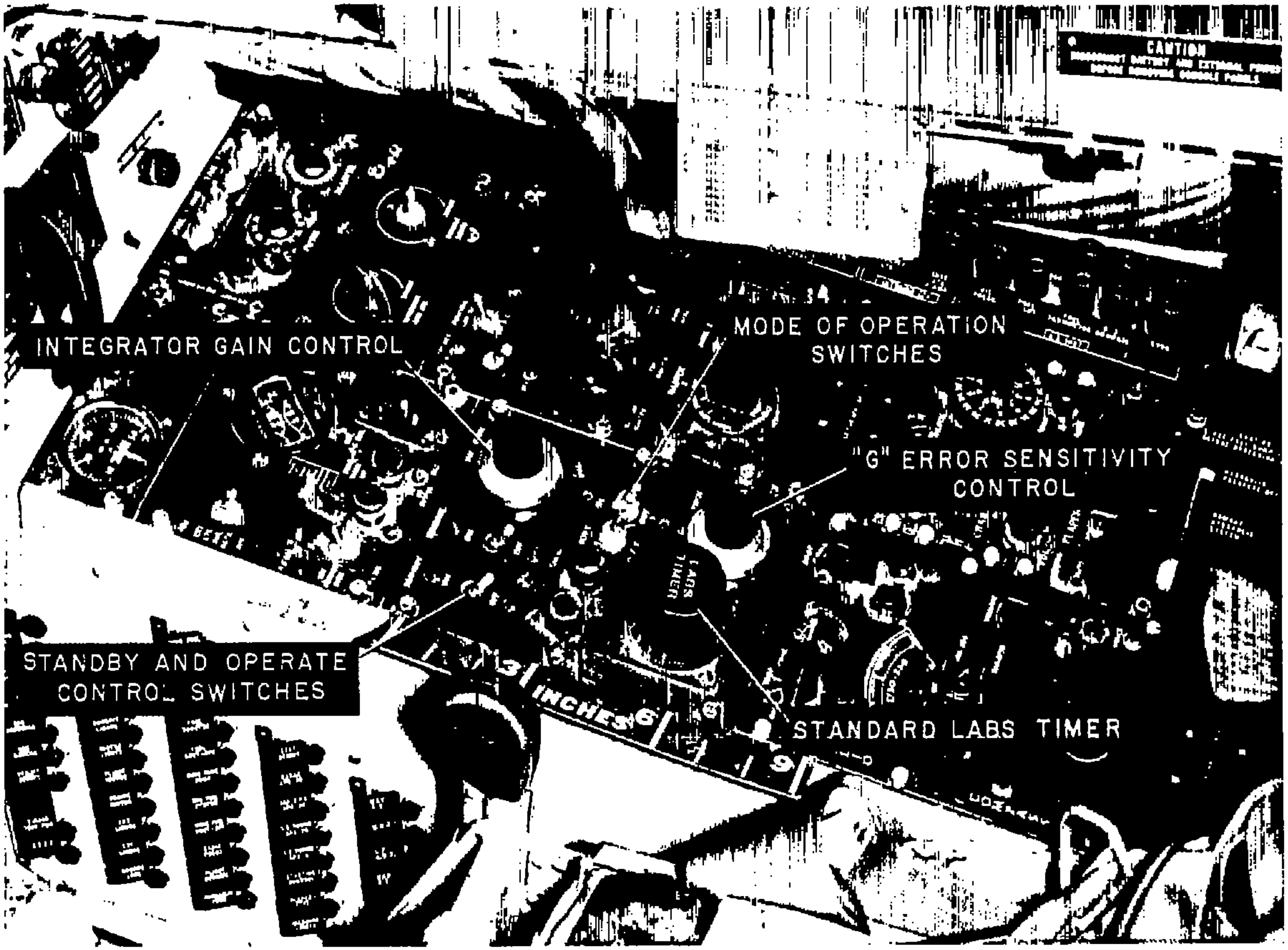


Figure 9.- Detail view of the right-hand cockpit console of the test airplane showing the installation of the pilot's control panel.

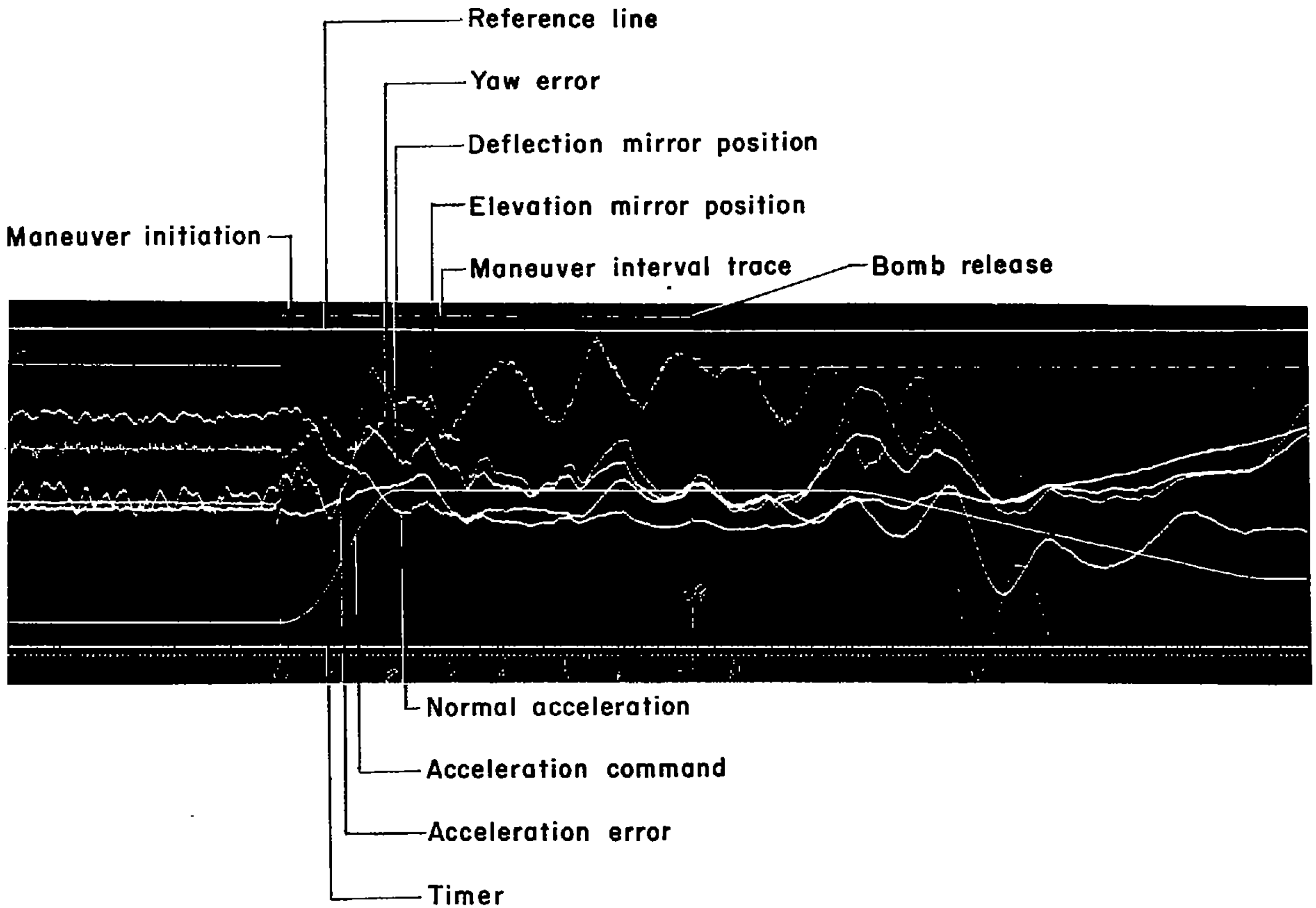
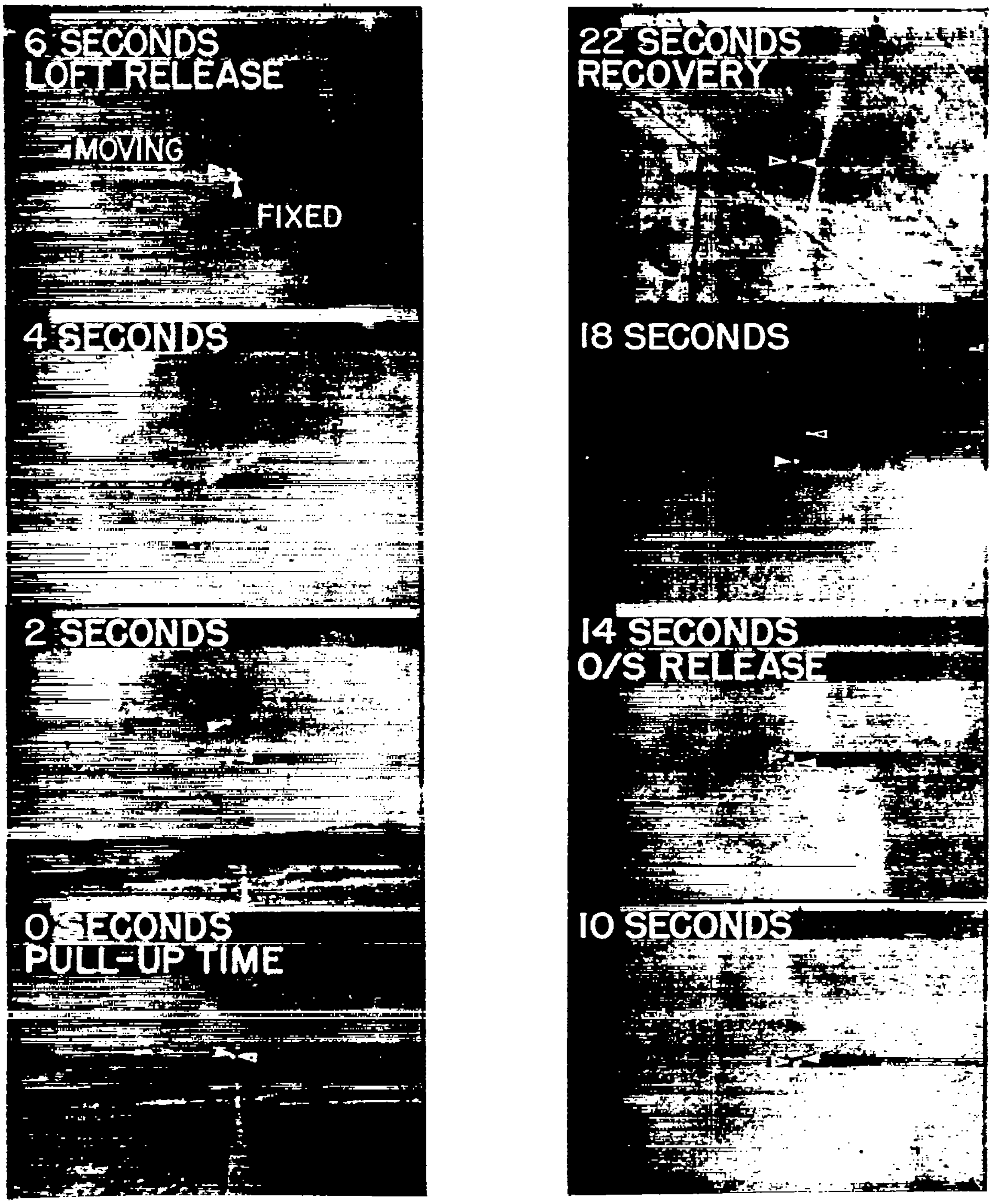


Figure 10.- Typical color oscillograph record of low-altitude bombing loft maneuver.



A-21931

Figure 11.- Selected frames from a movie taken with the GSAP camera during a typical low-altitude bombing maneuver.

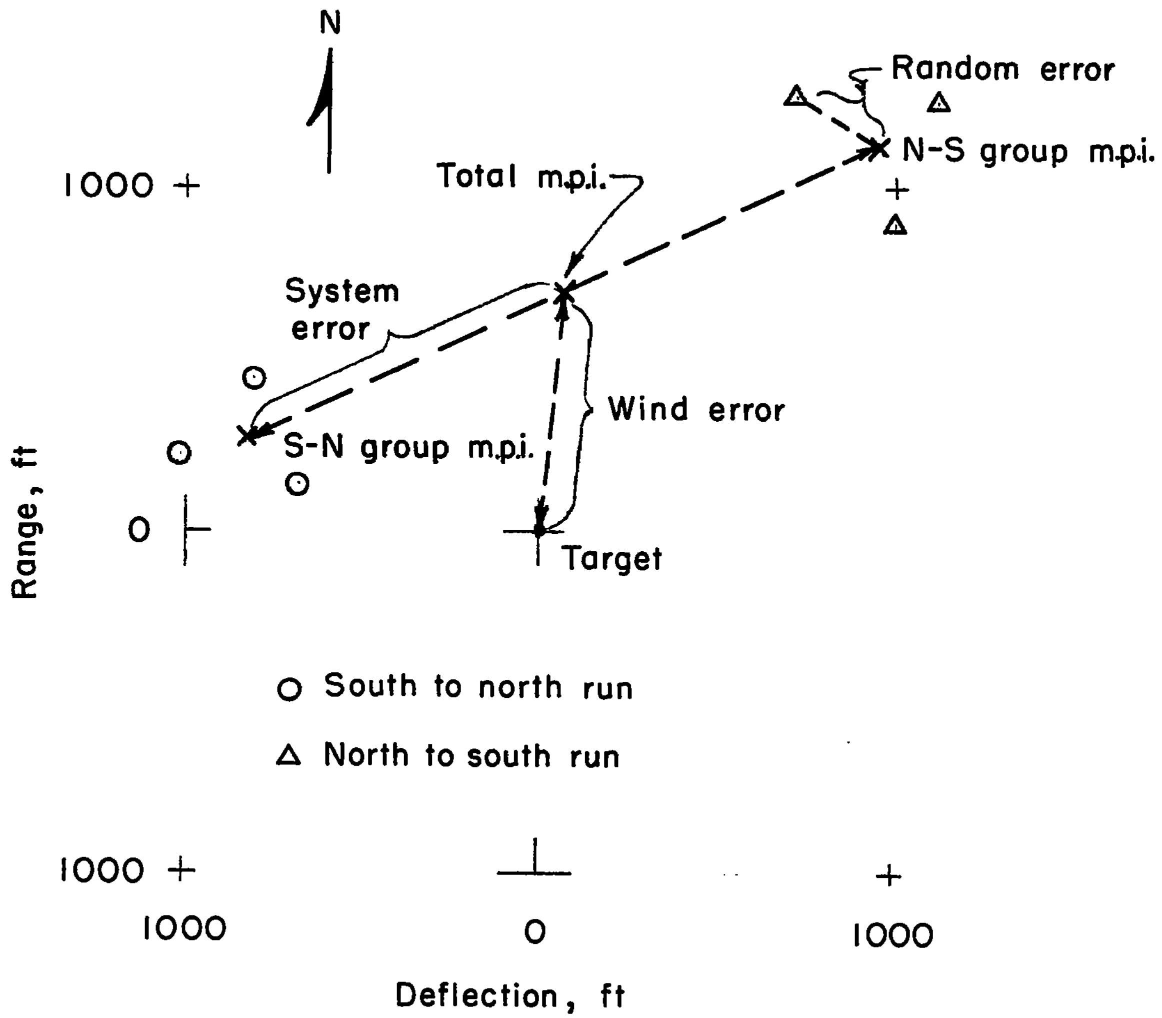
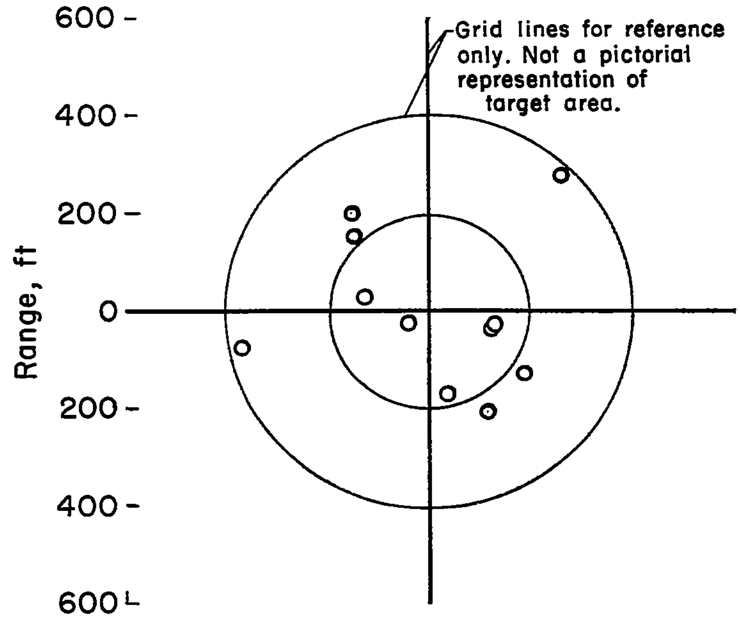
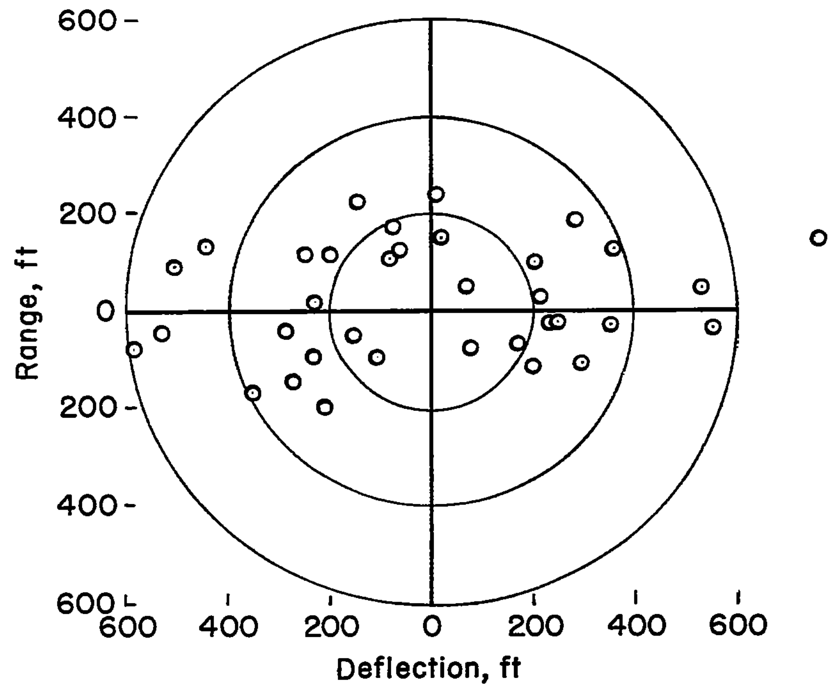


Figure 12.- Example bomb plot illustrating various bombing-error factors.

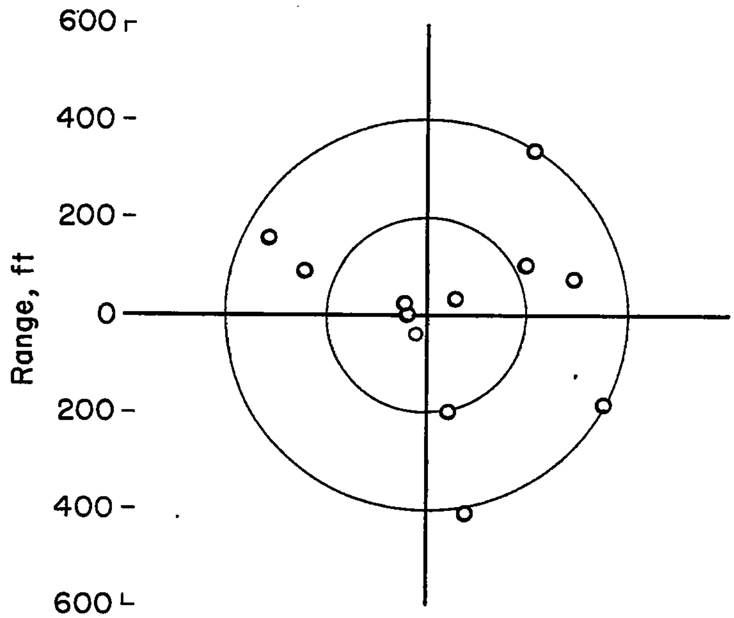


(a) O/S; integrator out.

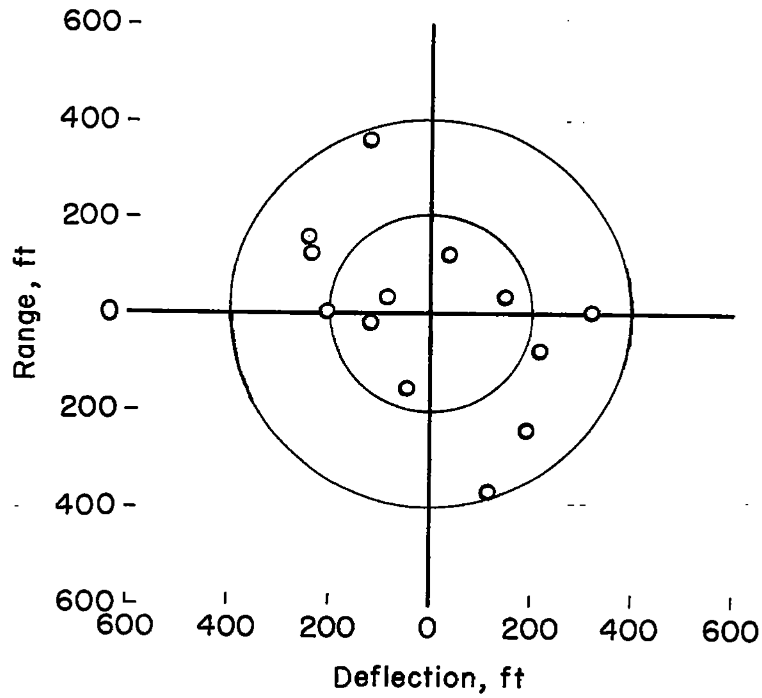


(b) O/S; integrator in.

Figure 13.- Plots of bomb impact points referred to the group mean point of impact.

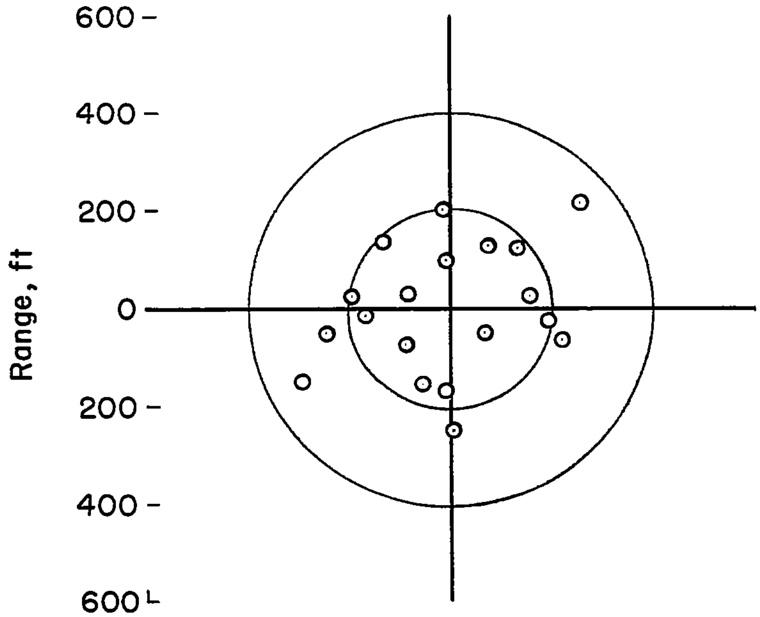


(c) Loft; integrator out.

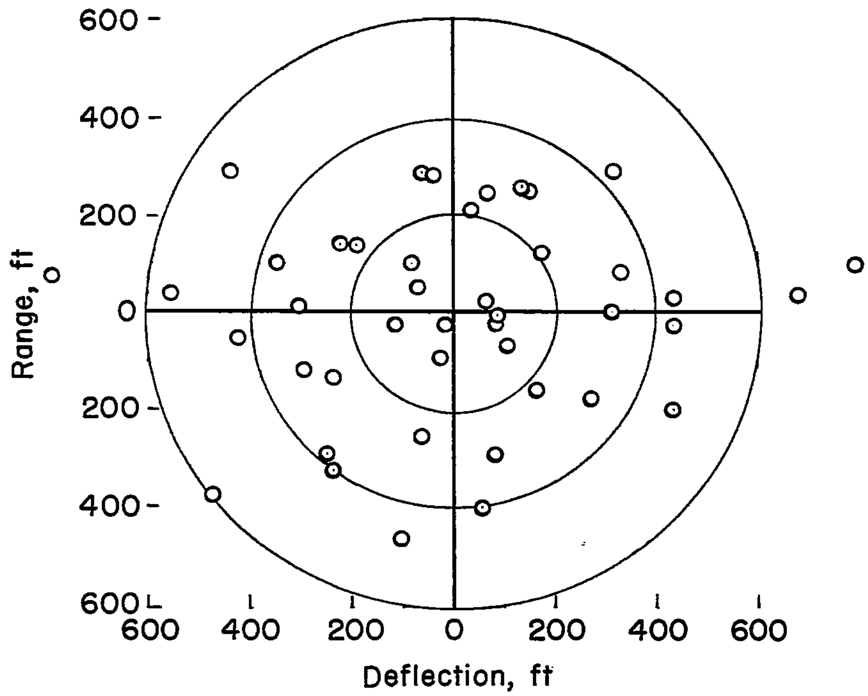


(d) Loft; integrator in.

Figure 13.- Continued.

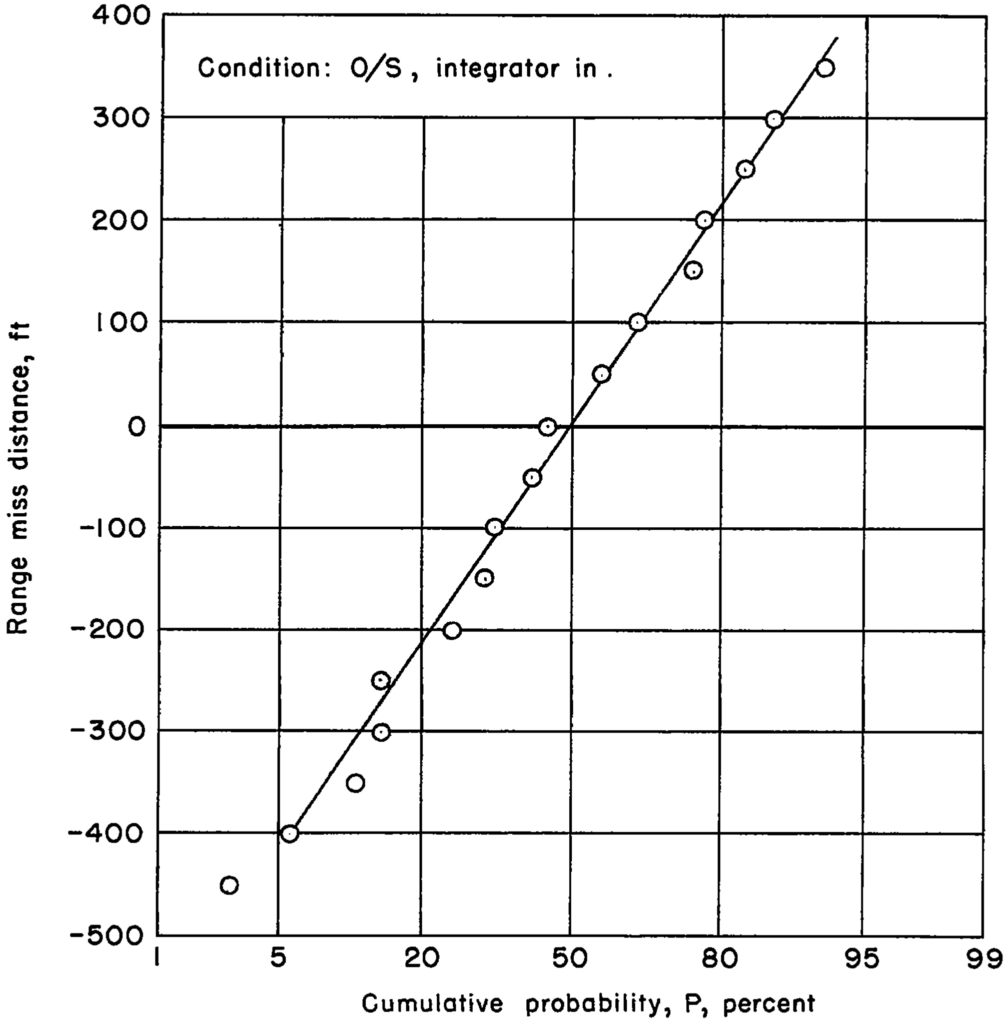


(e) Loft; standard system.



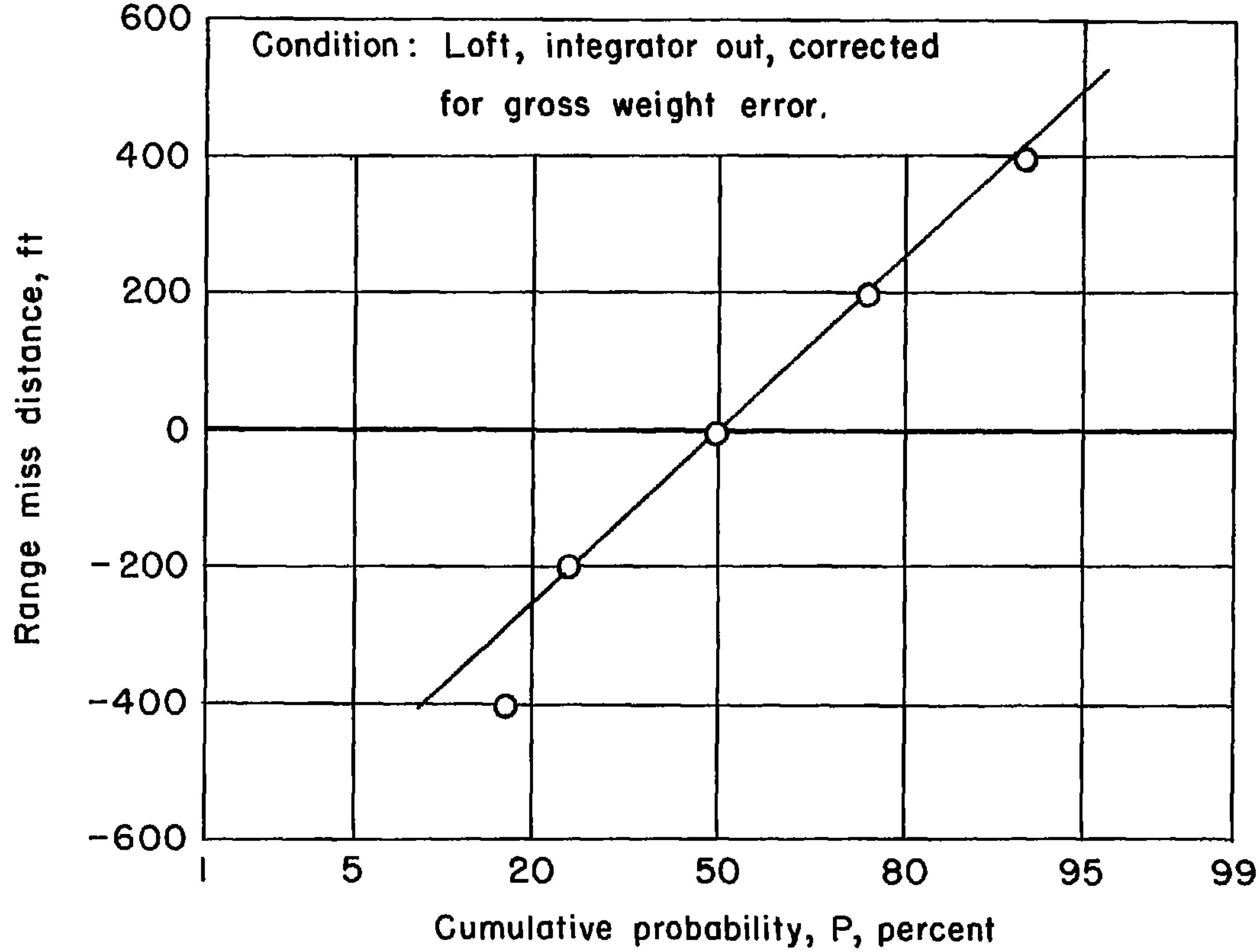
(f) O/S; standard system.

Figure 13.- Concluded.



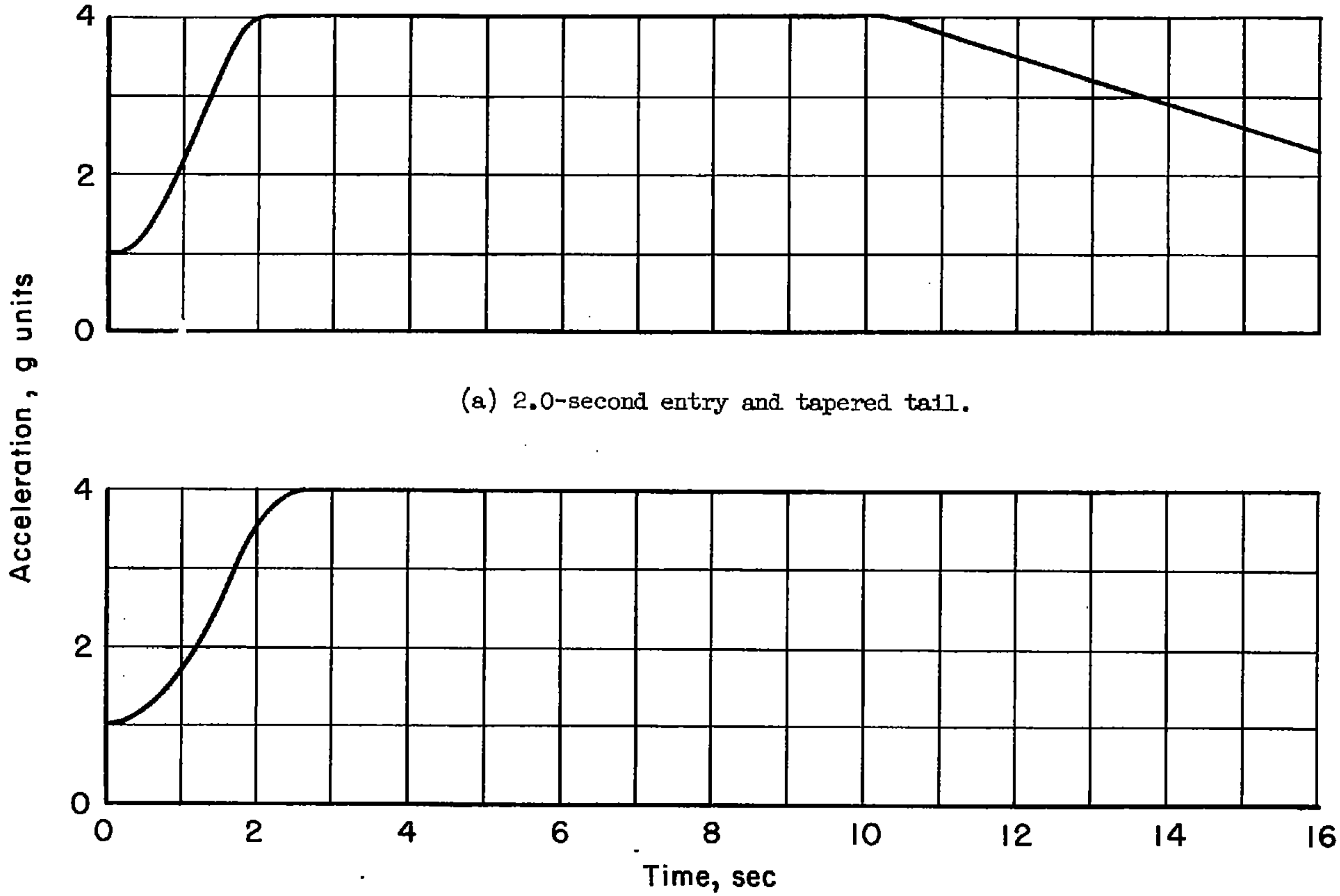
(a) Thirty-six test drops.

Figure 14.- Example probability plots.



(b) Eleven test drops.

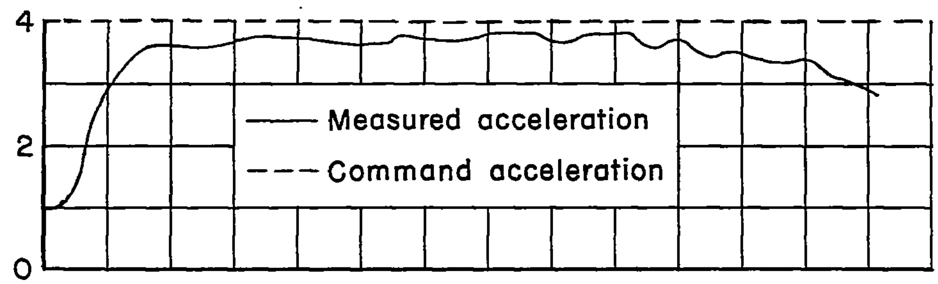
Figure 14.- Concluded.



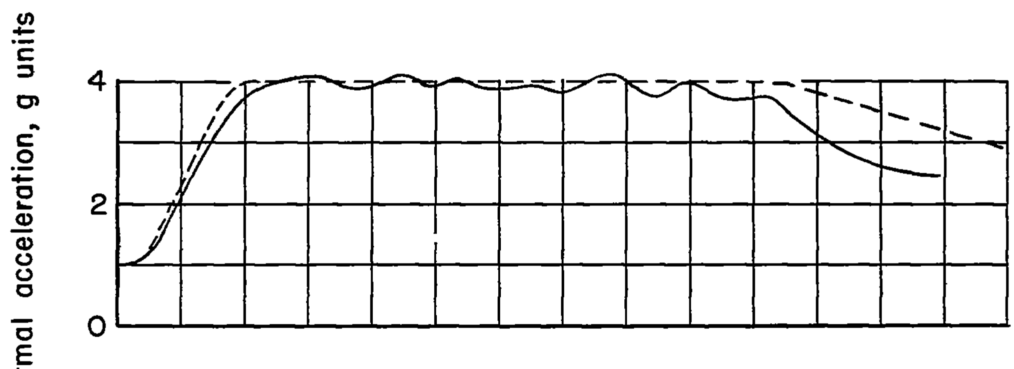
(a) 2.0-second entry and tapered tail.

(b) 2.5-second entry.

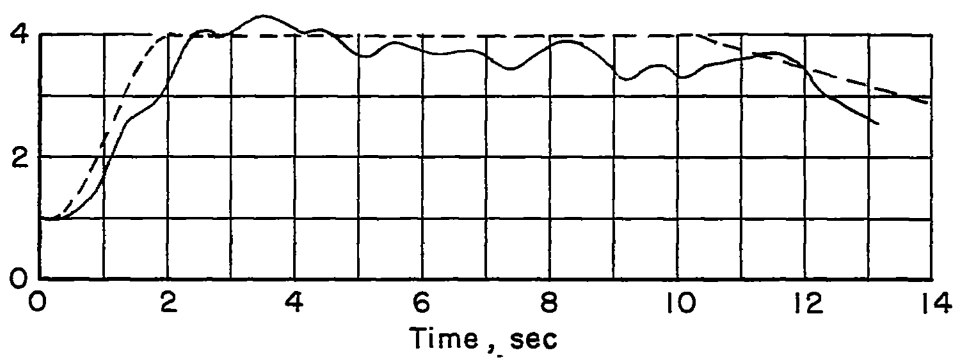
Figure 15.- Acceleration-command cam profiles.



(a) Standard system, smooth air.

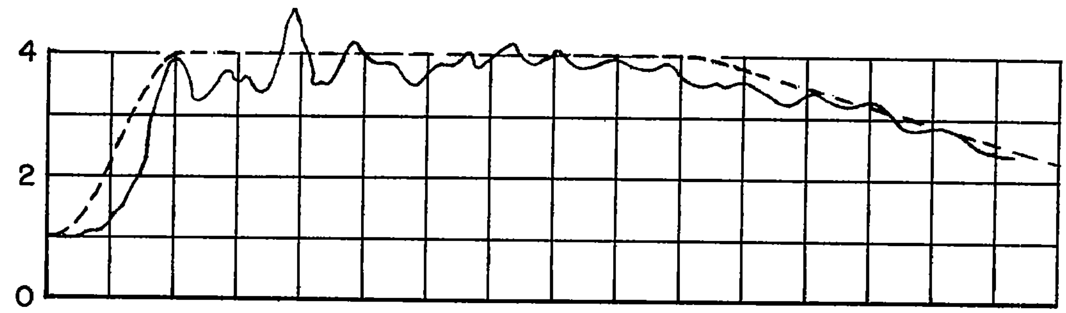


(b) Windshield display, integrator out, smooth air.

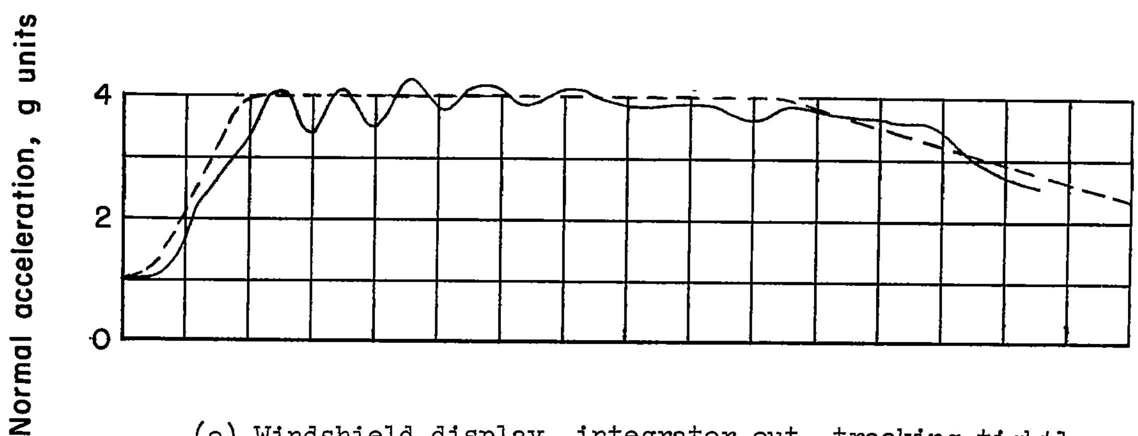


(c) Windshield display, integrator in, smooth air.

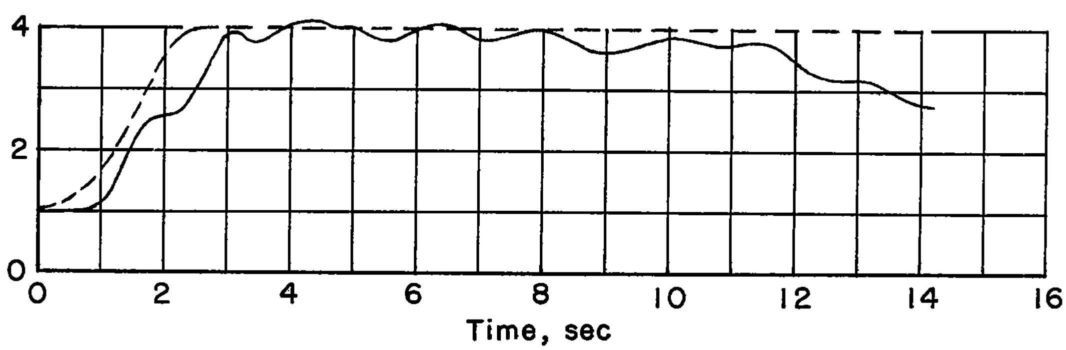
Figure 16.- Typical variations in normal-acceleration tracking performance.



(d) Windshield display, integrator out, rough air.

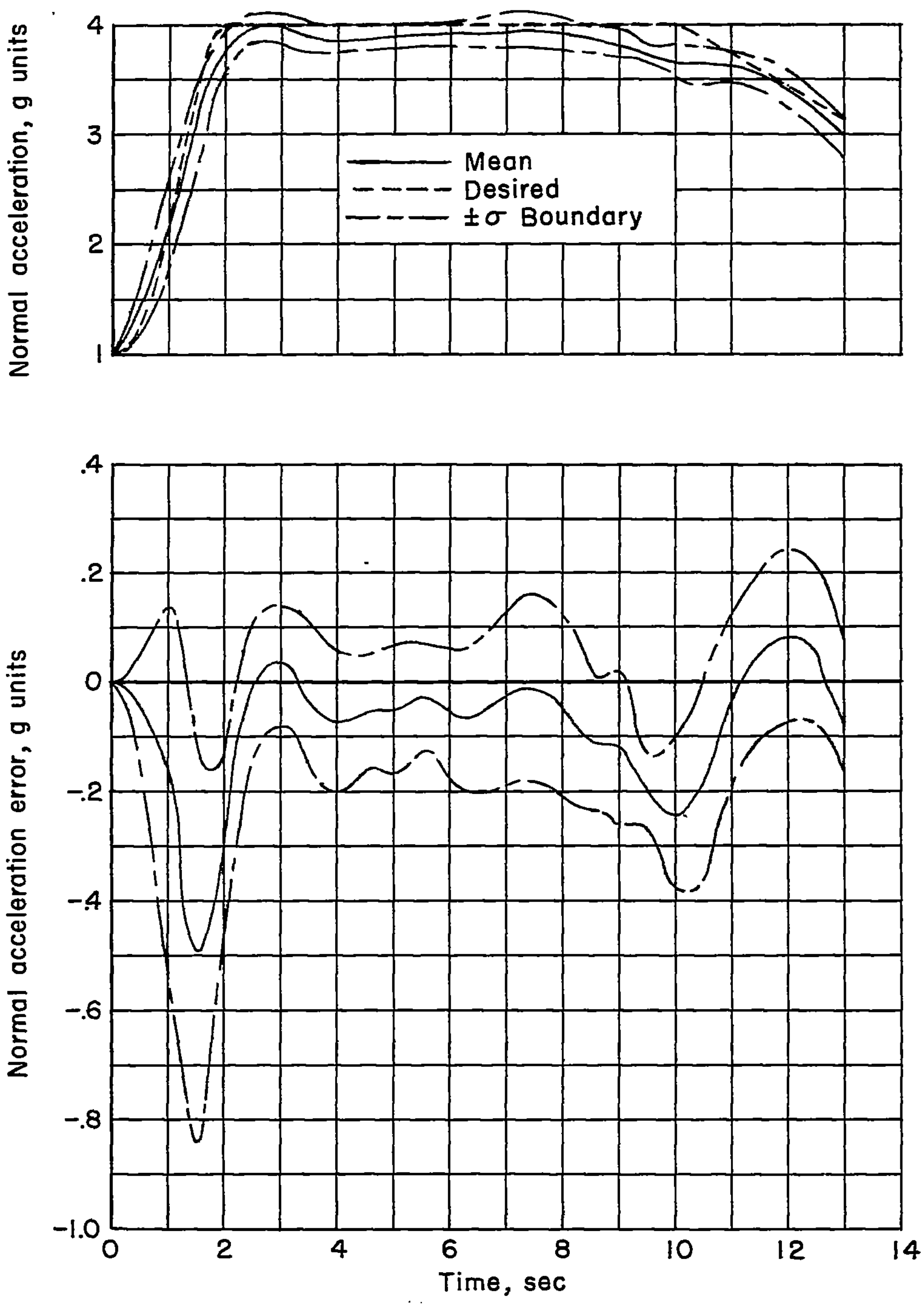


(e) Windshield display, integrator out, tracking tightly.



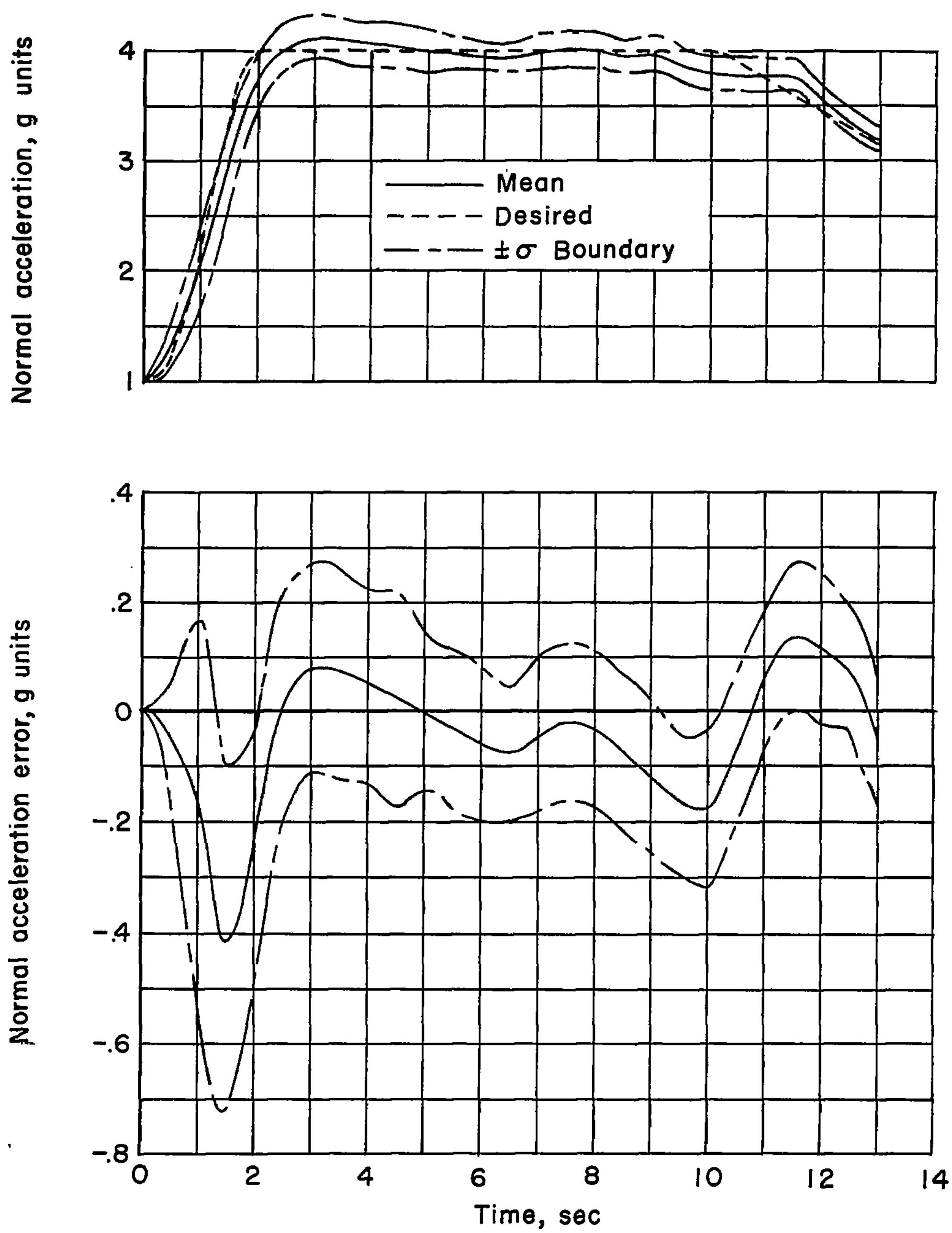
(f) Windshield display, integrator out, 2.5-second entry.

Figure 16.- Concluded.



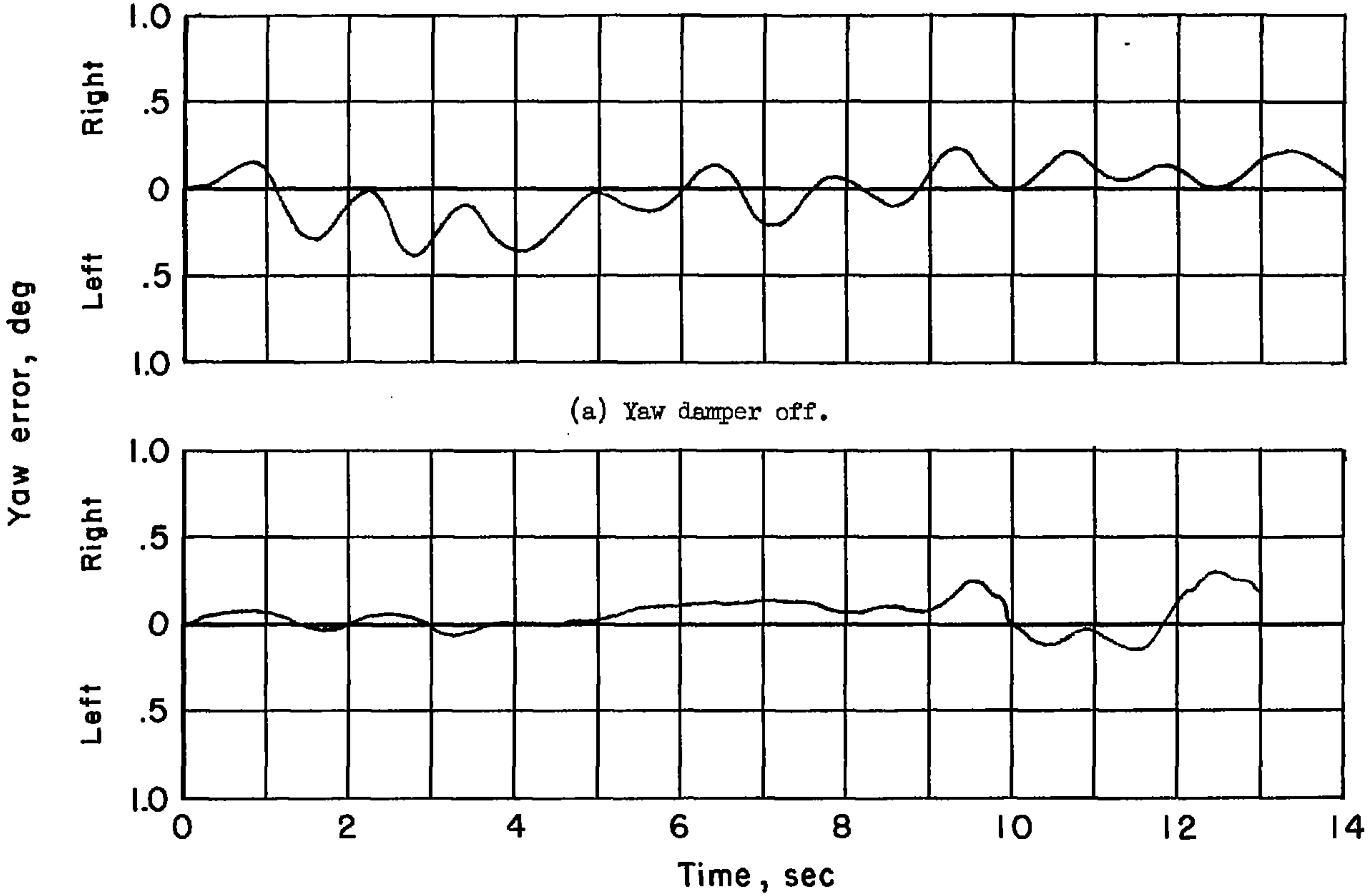
(a) Integrator out.

Figure 17.- Time histories of the mean normal acceleration with standard deviation boundaries.



(b) Integrator in.

Figure 17.- Concluded.



(b) Yaw damper on.

Figure 18.- Typical yaw-error time histories.